CARBON AND FOREST MANAGEMENT

Robert M. Clausen and Henry L. Gholz

School of Forest Resources and Conservation

University of Florida

Gainesville, FL 32611, USA

Technical Editor: E. Jean Brennan, Environment Center, U.S. Agency for International Development, Washington, D.C.

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Introduction

The United States Agency for International Development (USAID) is the principal U.S. Government agency charged with implementing the United States' international development and foreign assistance programs. Helping developing countries and countries with economies in transition to balance economic growth with environmentally sustainable development protects the global environment and serves the U.S. national interest. However, the threat associated with global climate change due to an increase of greenhouse gas emissions could severely damage international economic development and ecological balance. Thus, USAID is also committed to addressing the rapid buildup of carbon dioxide (CO_2), a major greenhouse gas in the atmosphere because, if greenhouse gas emissions continue to grow unabated, all sectors of the global economy, all natural ecosystems, and all countries of the world will be affected. The greatest costs, however, will be felt by developing and transition countries - those least able to cope with crisis and adapt to environmental changes.

The ability to "trap" CO_2 in the form of carbon through plant growth, particularly in forest ecosystems, is an important tool to combat the increase of atmospheric CO_2. This report is written primarily for USAID natural resource and environmental program officers, as well as for their host-country counterparts and other colleagues working on issues related to forestry. The report has two main objectives: (1) to synthesize existing information regarding the relationship between forest resources and carbon, as it relates to the issue of climate change; and (2) to provide the framework and guidelines for mission staff assessment of host-country trends and activities in relation to forests and carbon.

The report includes four main sections and eight Appendices. Section 1 describes carbon, its role in the environment, and how it is related to climate change. This section also provides a brief overview of the world's current and projected energy needs. Section 2 presents the relationship between forests and carbon, and introduces a range of forestry-related mitigation strategies. Section 3 summarizes the major international efforts taken to address climate change under the auspices of the United Nations. Section 4 provides guidelines for assessing the value of forest carbon at the mission level and is divided into three parts: assessing forest carbon at the national level, examining forest carbon links to mission programs outside the natural resources sector and estimating the forest carbon value of the natural resources program. This section contains suggestions for locating further information on these subjects, as well as for carrying out the assessment.

1.0 Carbon, Climate Change, Energy Demands and Sources

1.1 Carbon and Its Role in the Environment

Carbon is the building block of life. It has a unique ability to form strong bonds with itself and with other elements. This property allows carbon to combine with nitrogen, hydrogen and oxygen in nature to form the most critical compounds necessary for life (for example, CO_2 for photosynthesis, or simple sugars such as glucose, $C_6H_{12}O_6$; see Appendix 1 and 2 for additional information on carbon).

Carbon is found throughout the universe; on earth it is in the atmosphere, the biosphere, the hydrosphere and the lithosphere. It moves freely and readily throughout these reservoirs. Of particular interest for this report is how carbon moves between the atmosphere and the biosphere, and the two natural processes that are primarily responsible for much of this movement, photosynthesis and respiration.

The sun drives photosynthesis. During this process solar energy is absorbed by chlorophyll pigments inside leaves and is used to break down atmospheric CO_2 into its constituents. Carbon then combines with hydrogen and oxygen from soil water, along with other essential soil nutrients, to form carbohydrates, while the oxygen from the CO_2 is released back into the atmosphere. In respiration, carbohydrates are oxidized as part of the metabolic reactions for plant growth and maintenance, and carbon is released back into the atmosphere once again as CO_2 (Figure 1).

The natural global carbon cycle, which traces the flow of carbon, demonstrates its mobility within and between the four "spheres." Recent estimates indicate that 93% of all global carbon is found in the hydrosphere (most as dissolved inorganic carbon). Approximately 4% of the remaining 7% is found in the soil, and the atmosphere and aboveground terrestrial biomass contain 1.5% each (Watson 2000). In the biosphere, carbon occurs as organic molecules in living and dead organisms. Organic matter, or biomass (e.g., leaves, stems, roots, and logs), consists of approximately 50% carbon on a dry-mass basis (MacDicken 1999).

There are slight annual fluctuations in the natural global carbon cycle. Although these fluxes are small relative to the huge pools of global carbon, its accumulated increases or decreases in the amount of atmospheric carbon dioxide over centuries or even decades exert profound influence on global climate (Appendix 2).

1.2 Increasing Atmospheric CO_2 and Possible Effects on Global Climate

Greenhouse gases maintain a natural insulating layer around the earth, without which many forms of life unique to this planet would cease to exist (Appendix 3). CO_2 is the most abundant and important greenhouse gas. However, since the mid-nineteenth century the amount of CO_2 in the atmosphere has increased dramatically (about 30%), primarily as a result of human activities (Appendix 4). The emerging scientific consensus (first noted in Houghton et al. 1995) is that the increase of atmospheric CO_2, along with that of other greenhouse gases, is now undeniably affecting the earth's climate. Whether there has already been a measurable increase in surface temperatures is still uncertain (Santer et al. 2000).

Predictions of climate change impacts are even more uncertain at regional and local scales, but generally include increased incidence of extreme temperatures, as well as increased numbers and severity of floods, hurricanes, droughts, fires and insect outbreaks. If they occur, these events could have a positive feedback and further increase atmospheric CO_2, possibly resulting, for example, in higher rates of tree mortality and melting of permafrost in the tundra.

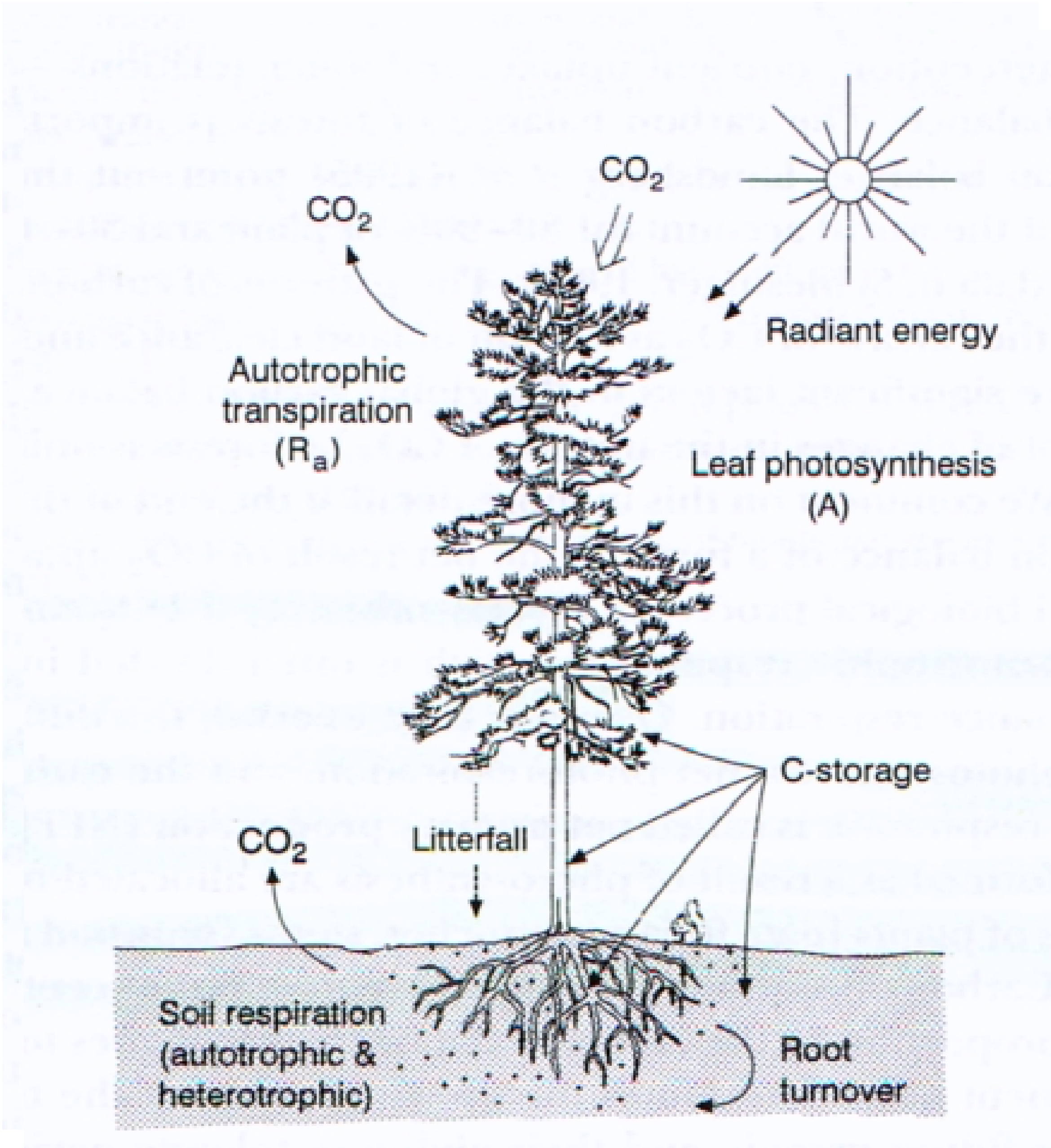


Figure 1. Schematic of the major elements of the carbon cycle for a forest ecosystem. Net primary production (NPP) is the difference between carbon fixed by the forest (gross primary production) and the respiration by all the living plant parts (above- and belowground) in the forest (NPP = GPP – Plant Respiration). Net ecosystem production (NEP) is NPP less the additional carbon released through the respiration of decomposers and other non-plant organisms in the forest (from Landsberg and Gower 1997).

The largest changes in the growth and composition of forests (Appendix 5) are expected to occur in the boreal (high-latitude) zones due to the expected greater warming at high latitudes. It is believed that many forest species in the boreal regions, particularly in the marginal zones, will be unable to adapt to suddenly warmer conditions or migrate at sufficiently high rates to avoid having to adapt.

Predictions are that a warmer climate would be generally characterized by longer and warmer growing seasons, milder winters and less permafrost. It would likely lead to a reduction in soil moisture during summer, which could increase the number of fires. In fact, it is speculated that potential temperature increases would have the most dramatic effects on fire frequency and insect outbreaks (Kirschbaum and Fischlin 1996).

The greatest change for temperate forests should be felt at the margins. With warming temperatures, temperate forests would advance northward into the boreal and maritime regions. In the south, particularly in drier inland areas, forests could be replaced by grasslands, which in the broader context could lead to a net carbon loss. Other negative effects could include an increase in the number and duration of droughts, and therefore increase in the incidence of forest fires. Warming could allow insects and pathogens to spread north, while those of the tropics and subtropical regions would have greater access to current temperate forests. Increased drought or extended periods of water stress would enhance the advancement of many pathogens and invasive plants.

Climate change is expected to affect tropical forests less than the boreal and temperate forests (Watson et al. 1996). However, climate change could decrease biodiversity at the edges of biomes and ecosystems. This is more likely to occur where human population pressures are greatest. Direct effects of elevated CO_2 concentrations in the atmosphere are difficult to ascertain in any ecosystem, although higher CO_2 levels could be a factor in observations of increased turnover rates (mortality - ingrowth; Phillips and Gentry 1994) and net carbon accumulation by primary tropical forests (Grace et al. 1995).

Genetic diversity could be crucial to the survival of populations that are being threatened by rapid changes in environment. The effects of climate change on genetic resources are not well documented but are receiving increased scientific attention. Climate change, in addition to ongoing destruction of alternative habitats through deforestation, would greatly reduce chances of species adapting to a rapidly changing climate (Bawa and Dayanandan 1998).

It is projected that desert ecosystems will become even hotter and drier, which could eventually lead to the extinction of species that already exist near the limits of heat and moisture tolerance (Noble and Gitay 1996). Other climate models suggest that between one-third and one-half of mountain glaciers, and substantial portions of the Polar ice caps, could disappear over the next 100 years (Johannessen et al. 1999). This would affect water flows and disrupt the supplies of food and fuel for populations of mountain people, especially in developing countries. Inland water systems would also be affected, along with their associated biodiversity (Benniston and Fox 1996).

Some of the largest changes are expected to occur in coastal zones, which not only have major global ecological and economic importance but also support a majority of the world's human population. Changes in these ecosystems could have serious effects on freshwater supplies, fisheries, biodiversity and tourism (Watson et al. 1996). Rising sea levels could lead to the destruction of coastal habitats, erosion of shores, and increased salinity of estuaries and freshwater aquifers. Some of the ecosystems at greatest risk include marshes, mangroves, coastal wetlands, coral reefs and river deltas. Compounding the problem associated with increased greenhouse gas emissions is the recent widespread destruction of mangrove forests throughout the world as they are cleared for fuelwood, building materials, and converted to shrimp farms and cropland (Brown 1999). The loss of this forested buffer zone leaves coastal areas more susceptible to flooding, wave impacts and impacts of severe storms (Watson et al. 1996).

How climate change will affect the oceans is a critical research question and area of study. Climate change could disrupt global oceanic currents, which are responsible for, among other things, bringing warmer water to the North Atlantic and North Pacific Oceans. These are known as the "conveyor belt" currents that moderate northern climates in what would otherwise be environmentally harsh regions (Figure 2). A sudden cooling of the Northern Hemisphere by a degree or so, for example, could produce unseasonably cold periods, droughts and floods (Kerr 1998). Ocean currents are part of an extremely complex system, and changes to that system could have profound implications for much of the world.

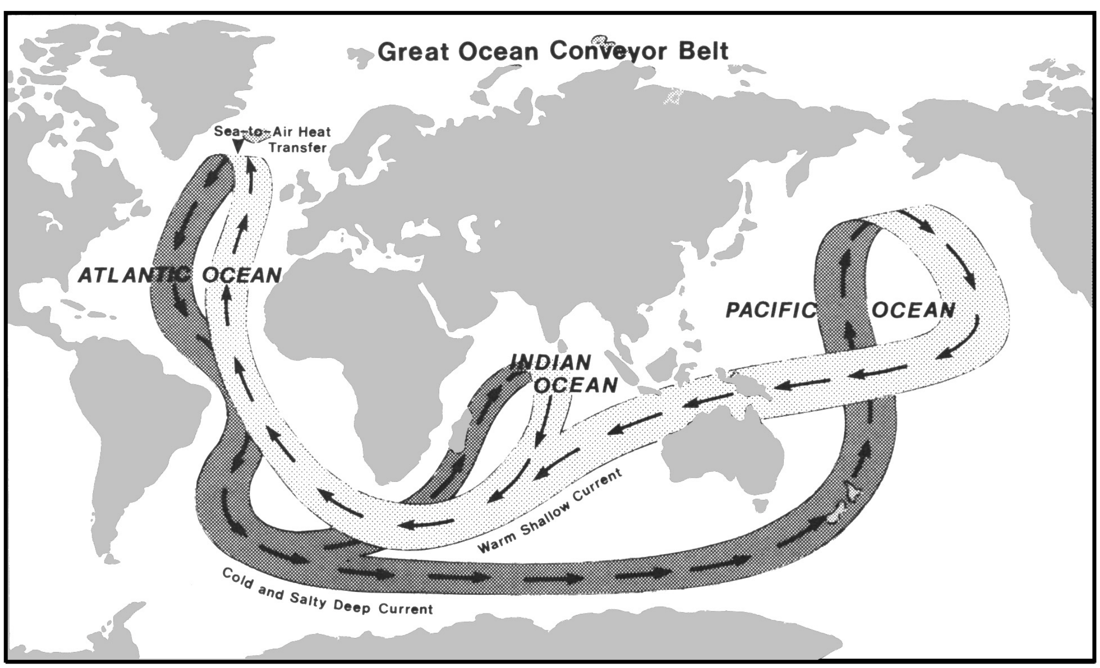


Figure 2. The linkages among global ocean currents (Conveyor Belt) as conceived by Broecker (1991).

The El Niño (1997–1998) and La Niña (1998–1999) clearly demonstrated that severe hardship and disaster can be brought to millions of people and around the world in just a short period of time by climatic fluctuations, regardless of the cause. The El Niño (or more correctly, El Niño - Southern Oscillation, or ENSO) is a natural periodic oceanic/ atmospheric phenomenon causing a large area of the equatorial basin of the Pacific Ocean to undergo alternating periods of heating and cooling. The most recent El Niño was one of the strongest in recorded history, leaving millions of hectares of forests throughout the world destroyed by fire or damaged by severe ice storms. Whether ENSO is being affected by human activity is not known.

As indicated above, the amount of CO_2 in the atmosphere has increased significantly since the mid-nineteenth century. Most of this increase (about 70%) is directly related to the increased use of fossil fuels in the energy sector. Wood was the world's primary energy source until 1860 and has since been replaced by coal and oil as the top source of energy.

1.3 CO_2 and the Energy Sector

Current fossil-fuel energy reserves that have been located and are exploitable with current technologies are estimated at about 50,000 EJ[1]. Coal constitutes about half of these reserves, with the rest divided about equally between gas and oil. At current consumption rates, the reserves will last another 130 years (Nakicenovic 1996). However, continued reliance on fossil fuels will assure increasing levels of atmospheric CO_2, with acceleration of climate change.

Table 1. Global annual energy consumption in 1990 by energy source, in Exajoules (EJ/yr; adapted from Nakicenovic 1996).

Source	**EJ/yr**
Oil	128
Coal	91
Gas	71
Biomass[2]	55
Hydropower	21
Nuclear	19
Other (solar, wind, geothermal)	<1
Total	**385**

[1] ***Work***, in a scientific sense, is the result of a force acting on a stationary body when that body is displaced. In international standard (SI) units, the force unit is the Newton and the length unit is the meter. Thus the work unit is the Newton-meter, or Joule (J). Therefore, 1 J is the work done by a constant force of 1 Newton when the body on which the force is exerted moves a distance of 1m in the direction of the force (Shortley and Williams 1971). ***Energy*** is the capacity or ability of a body to do work and is also measured in J. The J is a very small unit. To provide a sense of scale, 1 kilocalorie is equal to 4,184 J; 1 BTU (British thermal unit) is equal to roughly 1,000 J (or 1 kJ). On a global scale, Joules are presented in units

The world's energy needs are still largely met by fossil fuels (Table 1). Estimates of the global energy demand by the year 2100 vary from a low of 514 EJ/yr to a high of 2,737 EJ/yr (Nakicenovic et al. 2000), depending on which population growth and development patterns are projected. Where the additional energy will come from depends mainly on economics and the development of new technologies.

It is known with some certainty that about 70% of the increase in atmospheric CO_2 is a direct result of fossil-fuel use for energy. Most of the rest is attributed to deforestation in the tropics (Watson 2000), although this is still highly uncertain (Houghton et al. 2000). The greatest proportion of the CO_2 produced from fossil fuels derives from the developed countries. However, as countries develop their fossil-fuel consumption increases (Appendix 4).

There are, of course, many energy alternatives to fossil fuels, including solar energy, hydropower, geothermal and biomass energy. In an ideal world, their rapid deployment would be the most effective way to reduce CO_2 emissions. These alternatives hold great promise, and it is expected that they will eventually take on a much greater proportion of meeting the demand for energy. Unfortunately, each alternative has limitations that currently hinder broad global application, the main one in all cases being that they are more expensive per BTU than the use of oil or coal.

Hydropower is one of the most widely developed and employed non-fossil-fuel energy sources worldwide. Given current technology, its potential could be doubled within 25–30 years and longer-term projections are even more optimistic. However, ecological and environmental considerations point to more widespread use of mini- and micro-hydrological systems as opposed to more massive dams.

Technology exists to exploit geothermal energy, but source accessibility problems continue to limit production. Cost is the chief limitation to the widespread use of wind and solar energy. The sun provides the earth with about 5.4 million EJs on an annual basis, and capturing just a small fraction of this total could satisfy the world's energy needs indefinitely. However, cheaper fossil fuels will continue to limit use of wind and solar energy for the near future, even though advances in technology (e.g., photovoltaics) are rapidly leading to cheaper products (Nakicenovic 1996).

Biomass energy sources are considered "carbon neutral." Carbon neutrality essentially means that during the lifetime of the resource, carbon will be both taken up (sequestered) and released in relatively equal quantities. In the case of forest plantations for biomass production, the trees are taking up carbon from the time they are planted until harvest. Once the trees are removed, carbon is released back into the atmosphere through eventual decomposition or burning.

of exaJoules (EJ), equivalent to 10^{18} J. It takes just under 1 EJ of energy for New York City to function for 1 year. Global primary energy consumption in 1990 was estimated at 385 EJ (Table 1).

[2]About 90% of the biomass is collected directly from natural sources and used locally without being converted into fuels or electricity.

The key limiting factor in biomass energy production is the availability of land. Despite this constraint, the surface area covered by plantations is steadily increasing (due to demands unrelated to energy, i.e., pulp and fiber production), mostly in the tropics, where current estimates of available land range from 580 to 620 M ha. Biomass already provides about 55 EJ/yr to the global energy sector; this proportion could be significantly increased during the next 25 years (Nakicenovic 1996).

The other activity contributing to the atmospheric CO_2 buildup is the clearing and conversion of forests to other uses, which is taking place primarily in the tropics. Vast forested areas in Latin America, Asia and Africa are being cleared for agriculture and pasture. In many cases, residual forest materials are burned, leading to an immediate return of CO_2 to the atmosphere.

2.0 Forestry and Climate Change

2.1 Forest Management

Within the context of this report, the term "forest management" in the broadest sense is used to include any activity that is planned and implemented on a forested area. This could range from low-input strategies like strict preservation to the intensive management of plantations (Figure 3).

Historically, the term forest management implied a certain level of commercial timber exploitation taking place in a managed forest area. This is understandable, since up to the mid-twentieth century most forestry-related activities focused on timber values. By the 1960s ecologists, forest managers and others clearly articulated the fact that forests offer many more goods and services than just timber. On a policy level this led to the concept of multiple-use management, which has been a standard part of forest management planning and operations throughout the world ever since.

Multiple-use management (or a range of similar concepts, such as ecosystem management) recognizes that, in addition to producing timber and other commercial products, forests are valuable watersheds, support the world's richest areas of terrestrial biodiversity and provide very important social services and products, including a wide range of recreational activities (Costanza et al. 1997). More recently, forests are being acknowledged for their carbon value as it relates to ameliorating climate-change impacts.

At present, only about 11% of the world's forests are being actively managed with a long-term plan for goods and services. Most of this is taking place in the temperate and boreal countries (Appendix 5 contains descriptions of global forest types). The situation is far different in the tropics, where only 4% of forested lands are under management (Brown 1996).

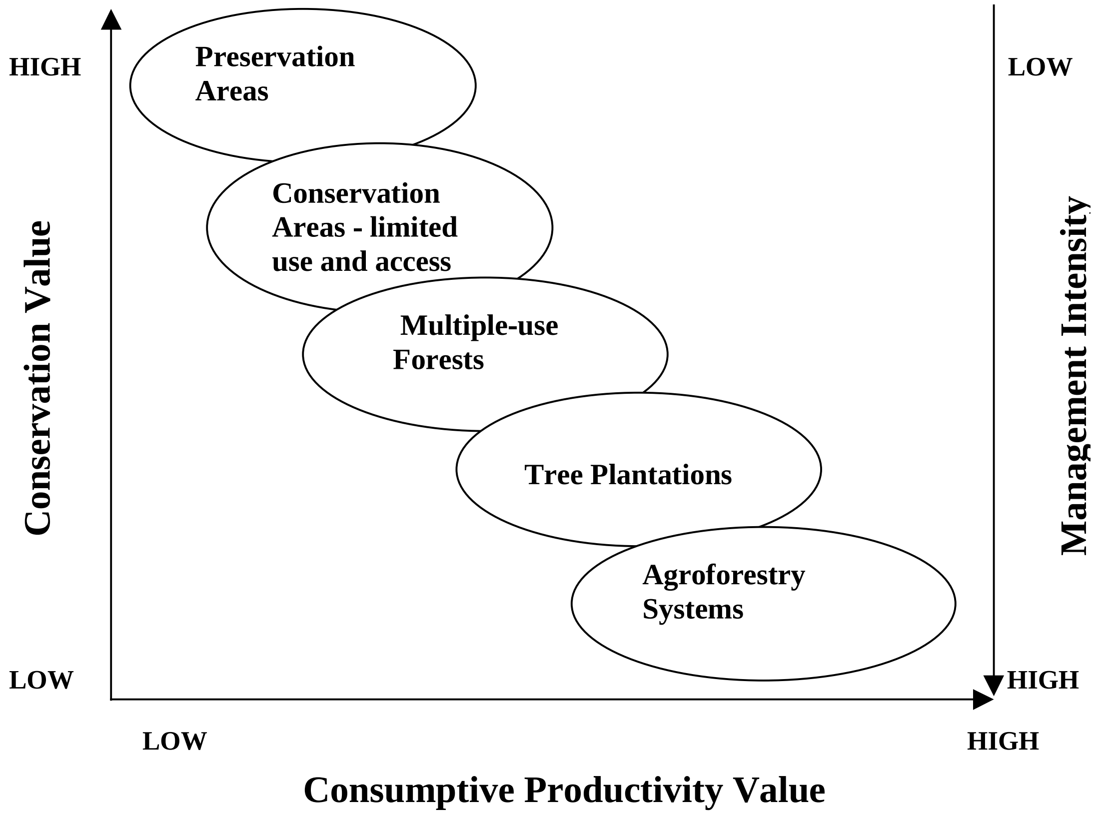


Figure 3. The production and conservation values of forests, ranging from natural stands, to plantations and agroforests, represented as a continuum (after Nambiar 1996).

2.2 Mitigation Strategies Based on Forest Management

A variety of approaches are available for increasing the size and number of terrestrial sinks for atmospheric carbon. Most of the current focus involves management of natural forests or establishment of tree plantations. Mature forests sequester carbon at slower rates (in kg C/ha/yr) than do young forests or even-aged natural stands. In carbon terms, the importance of maintaining mature forests derives from their high existing carbon contents in biomass (in kg C/ha). Old-growth (or other long-undisturbed) forests contain by far the greatest amounts of aboveground carbon per hectare in the terrestrial biosphere, compared with any other land cover. Once mature forests are removed, these valuable pools of carbon are lost to the site and are eventually released into the atmosphere through decomposition of residues and products, or oxidation by fire.

In contrast, younger forests and particularly plantations, accumulate (or sequester) carbon in biomass at much greater rates than old forests, although their total standing carbon contents at "maturity" (i.e., at the time of commercial harvesting) are usually relatively small compared to the amount found in a mature natural forest. Table 2 indicates the range of ecosystem (vegetation and soils) carbon stocks according to major biome.

Table 2. Global carbon stocks in vegetation and soils (WBGU 1998).

Biome	**Area** (10^6 km^2)	**Global Carbon Stocks (Gt C)** Vegetation	Soils	Total
Tropical forests	17.6	212	216	428
Temperate forests	10.4	59	100	159
Boreal forests	13.7	88	471	559
Tropical savannas	22.5	66	264	330
Temperate grassland	12.5	9	295	304
Deserts and semiarid areas	30.0	8	191	199
Tundra	9.5	6	121	127
Wetlands	3.5	15	225	240
Croplands	16.0	3	128	131
Total	**135.6**	**466**	**2011**	**2477**

Three broad forest management strategies can be used to mitigate the effects of global warming: (1) conservation of existing forests (e.g., improved silvicultural practices, forest protection from fire and disease; and sustainable forest management); (2) establishment of new forests (e.g., afforestation and reforestation, agro- and urban forestry); and (3) product substitution through an increase in the demand for wood products that could replace other more carbon-intensive materials (e.g., new products developed from wood waste, and biomass fuel to replace fossil fuels) (Appendix 6).

Conservation of existing forests could be achieved by reducing the rate of deforestation for land conversion, improving harvesting methods (i.e., more closely matching silvicultural systems to specific forest situations) and increasing forest protection from fire, illegal logging and other damaging agents. A dynamic strategy for existing forests would also incorporate methods to maximize other resource benefits, such as conservation of biodiversity and maintenance of intact hydrologic and nutrient cycles, while making more efficient use of limited financial resources. For carbon, one of the most promising areas is increased attention to biodiversity conservation and development of additional protected areas.

Creation of protected areas (e.g., national parks, preserves, conservation zones) has increased dramatically worldwide in recent years. Setting aside such areas usually translates into less extractive uses. Some countries have doubled or tripled the forested land area that is being brought under protected-area status (e.g., Uganda, Madagascar).

In principle, elevating the conservation status of a forested area increases protection, which in turn serves the interests of both biodiversity and long-term carbon storage.

Reforestation, afforestation and agroforestry efforts are often designed not only for wood production but also to protect valuable watersheds or to reduce soil erosion in mountainous areas. The objectives sometimes vary and could include improvement of wildlife habitat, wetland rehabilitation, or other environmental amelioration. Production forestry is often secondary to these other uses, which means that stands could sequester and store carbon for much longer periods than if timber production were the only objective. While these activities are not specifically designed to help sequester carbon, their cumulative effect in this regard could be significant. Combining objectives could produce additive advantages for a range of environmental functions, including improved capacity to sequester and store carbon.

The second strategy is establishment of new forests through afforestation, reaforestation, forestry, or urban forestry. Throughout the world, a great deal of what has been classified as afforestation and reforestation is the establishment of forest plantations. Compared with natural forests, plantations already produce a disproportionately greater amount of the world's forest products, a trend that may continue into the foreseeable future. Although plantations generally contain much less carbon in biomass than natural forests, they contain more carbon than non-tree cover area and sequester carbon at much higher rates per unit area (Gholz and Lima 1997).

A key point in calculating carbon benefits associated with tree plantations is that plantations should be established on previously non-forested land (afforestation) or on areas that were once forested but were subsequently converted to other land uses (reforestation). As biodiversity conservation is increasingly recognized for its importance, and awareness spreads that the world’s largest terrestrial carbon pools are found in natural forests, there will be increasing pressure to focus on afforestation and reforestation, as opposed to converting natural forests into plantations. Therefore, plantations are likely to play an increasingly important role in the management of forests for carbon storage. Unfortunately, plantation establishment has often been at the expense of natural forests. This in effect trades existing, extremely large and stable carbon pools for young plantations that may sequester carbon at high annual rates, but which contain relatively low levels of carbon in biomass and detritus. The tradeoffs are not obvious, but one study estimated that it would require at least four rotations (cycles of harvesting and replanting) of plantations with little decay of harvested wood products to offset the carbon lost from clearing an equivalent area of old-growth forest (Harmon et al. 1990).

With the world’s population rapidly expanding, people are trying to get greater productivity out of their land through more intensive agricultural and forestry techniques. One way to achieve this is by practicing agroforestry, where forest and food crops are integrated in spatial and temporal arrangements that increase the productive capacity of the land. In this context, the productive potential of agroforestry is becoming more widely recognized, and these systems are being tested and adapted throughout the world, particularly in less developed countries.

The potential for carbon to be stored in agroforestry systems has received only limited attention, but estimates are that these systems could play a significant role in the overall strategy to address global warming. Carbon storage is generally intermediate between forests and other land covers (e.g., row crops), and there is potential for enhanced soil carbon storage as well (Watson 2000).

The effects of population growth will also be seen in the world's rapidly expanding urban centers. In the urban environment, trees play an important dual role in relation to CO_2. First, as with other forest systems, urban trees store carbon. Second, and perhaps more important, urban trees moderate the microclimate. During warmer periods, trees shade and therefore cool dwellings, allowing the residents to use less air-conditioning and thus a smaller amount of energy for cooling purposes. Conversely, trees block winds and insulate dwellings during the winter months, which reduces the amount of energy needed for heating. If these energy demands are being met by through fossil fuels, the carbon benefits associated with urban trees can be substantial. Forests also absorb considerable solar energy, using it largely for evapotranspiration, which additionally cools surfaces beneath them. These factors together can lead to a significant reduction in fossil-fuel use in urban areas with significant forest cover.

The third forest management strategy is to transfer a greater proportion of forest biomass into product substitutes for fossil fuels, i.e., increasing the use of wood products that store carbon and of other products that could replace materials requiring more energy to produce. Forest biomass already contributes significantly to the world's energy demands (Table 1). This trend could increase, especially with the establishment of additional tree-planting activities on marginal and degraded lands. With proper management, sites are prepared and replanted soon after the forest crop is harvested, thus minimizing the time that the land is not actively accumulating carbon.

Increased use of wood waste and other fiber sources in long-lived wood products is seen as another way to "lock up" carbon over long periods of time. The rate of decay of wood products is highly variable and depends on the material and how it is stored and used. Products such as newsprint, fuelwood, paper, plywood and timber all receive different drying and preservation treatments that will affect their ultimate durability and rate of decay.

The capability of soils to store additional carbon is of increasing interest, especially as molecular biologists are discovering the genes that regulate carbon translocation to roots. If more photosynthetic carbon can be transferred to roots, it may eventually be possible to manipulate either the species of vegetation or the genetic makeup of selected species to force the movement of more CO_2 from the atmosphere to longer-lived humic compounds in soil. Under current forest management practices in the temperate region, there is little evidence that the manipulation of forests (e.g., clear-cutting and regeneration, at the extreme) affects the amount of carbon is soil organic matter, unless forests are permanently cleared and/or areas are tilled for agriculture (in which case soil carbon generally decreases over time; Fearnside and Barbosa 1998).

3.0 Principal Actions to Date Regarding Global Climate Change and Forest Management

Literally hundreds of government agencies, universities, research institutions, foundations and non-governmental organizations (NGOs) throughout the world are engaged in activities related to the global carbon cycle and its connections to climate change. The only ones mentioned here are the United Nation's umbrella initiatives that have been designed to better coordinate and communicate multinational climate-change activities. Additional reviews and analyses of these and other international climate-change activities can be found in the public educational materials offered by other organizations, including the Atmosphere Radiation Measurement Program (U.S. Department of Energy) www.arm.gov/; the Woods Hole Research Center www.whrc.org/science/carbon/carbon.htm; the Carbon Dioxide Information Analysis Center www.cdiac.esd.ornl.gov/home.htm/; the World Bank Group–Global Climate Change www.esd.worldbank.org/cc/; Earth Observatory (NASA) http://earthob.nasa.gov/study/BOREAS; the International Geosphere-Biosphere Program (IGBP) www.igbp.kva.se/; the Global Change and Terrestrial Ecosystem project (GCTE) www.gcte.org/; and the German Advisory Council on Global Change www.wbgu.de/wbgu_home_engl.htm/.

With the backing of the international community, the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP) joined forces in 1988 to create the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess scientific, technical and socioeconomic information relevant to understanding the risk of human-induced climate change and to advise policymakers. It does not carry out research nor does it monitor climate-related data. The first major climate assessment of the IPCC (the "First Assessment Report" or FAR) was completed in 1990 (Houghton et al. 1990). This report served as the foundation for the development of the United Nations Framework Convention on Climate Change (UNFCCC).

The IPCC produced its Second Assessment Report (SAR) of three volumes in 1995 and presented it to the UN assembly. The report was published for general distribution the following year (Houghton et al. 1996, vol. 1; Watson et al. 1996, vol. 2). The SAR updated the initial report and further evaluated some of the technological issues and more recent developments related to the economic aspects of climate change. The IPCC also produced a Special Report in November 1997 titled "The Regional Impacts of Climate Change." Utilizing additional information made available since 1995, this report consists of vulnerability assessments for ten regions that comprise the earth's entire land surface and adjoining coastal seas. The IPCC's Third Assessment Report was released in January 2000.

In addition to the Assessment Reports and Special Reports, the IPCC has produced technical papers, standard methodologies and other products, which have become reference works used by scientists, policymakers and other experts. These can be accessed at www.unfccc.de/ or www.ipcc.ch/.

The 1992 UNFCCC is an international agreement to support the objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Negotiated over a period of two years, the treaty was signed and ratified by more than 160 countries and entered into force on March 21, 1994. The United States is a signatory, but has not ratified the agreement.

4.0 Assessing Forest Carbon at the Mission Level

There are many ways to measure forest carbon and Appendix 7 contains general information regarding the various techniques and their application. This section focuses on forest carbon assessments at the USAID mission level and is designed to assist the staff with reporting requirements associated with the USAID Climate Change Initiative (CCI). Specifically, this section can be used to help the missions report on programmatic results to achieve "<u>Reduced Net Greenhouse Gas Emissions from the Land Use/Forest Management Sector.</u>" It provides guidance regarding where to look for information within countries and how to enhance their reporting to better reflect the relative importance of each activity within the context of a mission's environmental programs.

Most nations in the UN General Assembly have signed the Kyoto Protocol under the UNFCCC which would establish legally-binding emission targets for the developed countries that are Parties to the Convention, and are already considering the steps necessary to carry out their commitment in achieving their emission reduction targets. USAID missions have the opportunity to facilitate the development of partnerships between host governments, private investment organizations and entities within the developed countries interested in supporting carbon-offset projects as a way of helping the country meet its target. If successful, such alliances could ultimately take the monitoring and reporting burden off the missions and lessen the missions' dependence on organizations and contractors.

With this guide, mission staff can help develop in-country capacity to monitor and assess carbon and forestry issues within universities and/or national environmental agencies. Such initiatives could take the form of a forest carbon database center, housed within a permanent institution that has a mandate for and an interest in keeping this type of information current. The center could either be self-sufficient or part of a larger activity linked to climate change, biodiversity, land-use practices or other related sectors. The center could also be responsible for monitoring forest management and carbon issues, assisting in research design, disseminating information to appropriate agencies and training groups and organizations to better understand and monitor these issues in the field. Mission assistance could be in the form of start-up funds, equipment, training or any combination thereof.

4.1 <u>Assessing Trends within Host Countries using Local and National Reports</u>

Assessment of national programs can be divided into two parts. The first involves assembling a set of brief local reports, each of which will list the forest resources within the area and describe major ongoing or planned activities that may affect the status of such resources. The second involves compiling a whole-country report, which will synthesize the main findings of the local reports and highlight key issues for mission consideration.

The first step in the assessment of national programs is obtaining a clear picture of the type and extent of forest resources within each country. This requires assembling reasonable quantitative estimates of the forest resources by biome type and land use. The Climate Change Initiative reporting documents provide a list of natural ecosystems, (including seven very similar to the biomes used in this report in Appendix 5) and managed ecosystems.

Most of this information is normally available as part of forest inventories, biomass studies or other surveys conducted by national and local organizations responsible for forest resources (e.g., forest services, park services, agriculture, and environmental agencies). It can also be found in government agencies associated with land-use planning and cartography, and even in local government archives (e.g., records of private forest holdings).

Many international organizations, such as the U.S. National Aeronautical and Space Association (NASA) Pathfinder Project and the International Geosphere - Biosphere Program's (IGBP) Land-Use and Forest Cover (LUCF) project, now monitor specific regions or countries. Other sources for this information could include agencies responsible for economic development (agencies engaged in commerce, import/export, or other similar activities), national and international NGOs, or bilateral and multilateral donor organizations.

At the local level, each country has geographic administrative units that are generally viewed as having the greatest level of autonomy relative to the central government. These are usually states, provinces, districts or similar units. Some degree of planning and development takes place at these levels, particularly in relation to natural resources. It is important to identify the operational level for development of local forest carbon assessment reports.

Once baseline information (i.e., extents and types of forest biomes/land uses) is compiled, efforts should concentrate on determining the relevant past, current and future activities associated with forests in these areas. For example, within the context of forest management activities could range from strict preservation to selective cutting, and even to complete removal of the forest cover (clear-cutting followed by conversion to non-forest uses). Local initiatives, such as community forestry, agroforestry, watershed protection or urban forestry, could also be included. The rationale and planning associated with a particular activity should be considered as well (e.g., the approval process, and the use of management plans and guidelines). Such efforts will provide a better understanding of the economic and social factors that help drive decision making at this level.

Other important considerations for the local reports include the roles and responsibilities of government and non-government organizations (including the private sector) involved in execution of the activities. Some organizations will be responsible for planning and authorization of on-the-ground activities, others with implementation. Some may have a strictly regulatory mandate or a combination of several key responsibilities. Each local report will clearly state the relationship between institutions and activities.

The political environment also will be taken into consideration. Are policies in place that encourage or discourage sound forest management? If policies exist, does enforceable legislation exist to support them? How do these reflect what is taking place on the ground?

Finally, are there reliable ways to regularly determine how these and other issues affect forests? Have monitoring and evaluation (M+E) systems been developed and placed into operation within these organizations? If time and resources permit, it would be beneficial to see what is being monitored and how often monitoring is carried out. If an M+E system is not in place, missions can examine what can be done to establish one.

In summary, the following issues will be addressed in local reports:

1. Extent, types and distribution of forest biomes and forest land-use systems
2. Past, present and future activities associated with these systems
3. Roles and responsibilities of organizations working with forest systems
4. Effects of the political and legal environment on forest systems
5. Efforts to monitor and evaluate the status of forest systems

The local reports will form the basis for the final country report, containing a summary of local report findings and assessments of the impacts of national and international issues affecting the country's forest resources. The country report should highlight key areas (strong carbon sources/sinks, storage areas) and the main issues related to management of forest resources. The final country report should also specify how these issues relate to the strategic objectives of USAID and make appropriate recommendations for possible follow-up action. The local/country assessment could be conducted once every 3–5 years.

4.2 Assessing Non-Natural Resource Activities within Mission Programs

Programs related to forest resources, which may have impacts but are outside that sector, could include activities in agriculture, health, education, democratization and private-sector development, among others. Following is a sample of questions that the mission Environment/Natural Resources (E/NR) Officer could ask in relation to other mission programs:

- Are forests being cleared for other objectives (agriculture, urban development)?
- Is private-sector promotion developing activities that exploit the forest resource base in an unsustainable manner?

- Is road rehabilitation leading to deterioration of forest resources?
- Is the mission affecting policies that promote or inhibit conservation of forests?
- Are climate-change issues being incorporated into educational curricula or extension-related materials targeted at a wider audience?
- Are decentralization initiatives leading to rapid liquidation of local forest resources?
- Are disease eradication programs leading to removal of forest cover?

Each program within the mission could then be assessed as to whether its activities promote forests as carbon sources or sinks, or are carbon neutral.

This approach has several benefits. First, it is a relatively rapid process that will indicate whether USAID-sponsored activities are contributing to or detracting from the Climate Change Initiative objectives. Once the initial assessment is completed, it would be relatively simple to revisit on an annual basis for monitoring purposes. Second, it can serve as a planning tool for other programs. If a program is weak, or promotes strong carbon releases rather than sequestration, mitigation of this impact could become a priority, resulting in redesign or modification of particular initiatives. Even if no immediate action is taken, the process will serve to signal a relationship or trend that warrants more regular monitoring.

4.3 Assessing Forest Management/Carbon Interactions within Mission E/NR Programs

As indicated earlier, different forest biomes have varying degrees of carbon storage and sequestering capabilities. Figure 4 illustrates the range of carbon in biomass and the rate of annual net biomass productivity (or the net carbon sequestration rate) among the world's principal terrestrial ecosystems, many of which are found in countries where USAID missions are present and have ongoing E/NR programs.

Most of the actions that need to be completed in relation to a mission's E/NR program are accounted for under the CCI indicators. This section contains additional information intended to further clarify the relative importance of various forest systems in relation to carbon storage and accumulation. It provides a simple tool to rapidly assess carbon storage and accumulation values for a range of forest systems (Table 3).

Only carbon that exists in the aboveground vegetation or that is fixed in aboveground biomass in one year is considered in the accounting scheme initially presented in Table 3. As discussed above, soils (including litter layers) and roots can contain large amounts of carbon as well. However, the greatest changes in the carbon balance of forests subject to any kind of manipulation will be associated with changes in the aboveground vegetation. Other aspects of the forest carbon balance are discussed in the Appendices to this report.

Average values of carbon storage and accumulation are presented in Table 3 for the forest biomes or forest systems, and are used for most of the calculations. The range of values typically associated with these biomes/systems is included in parentheses next to the

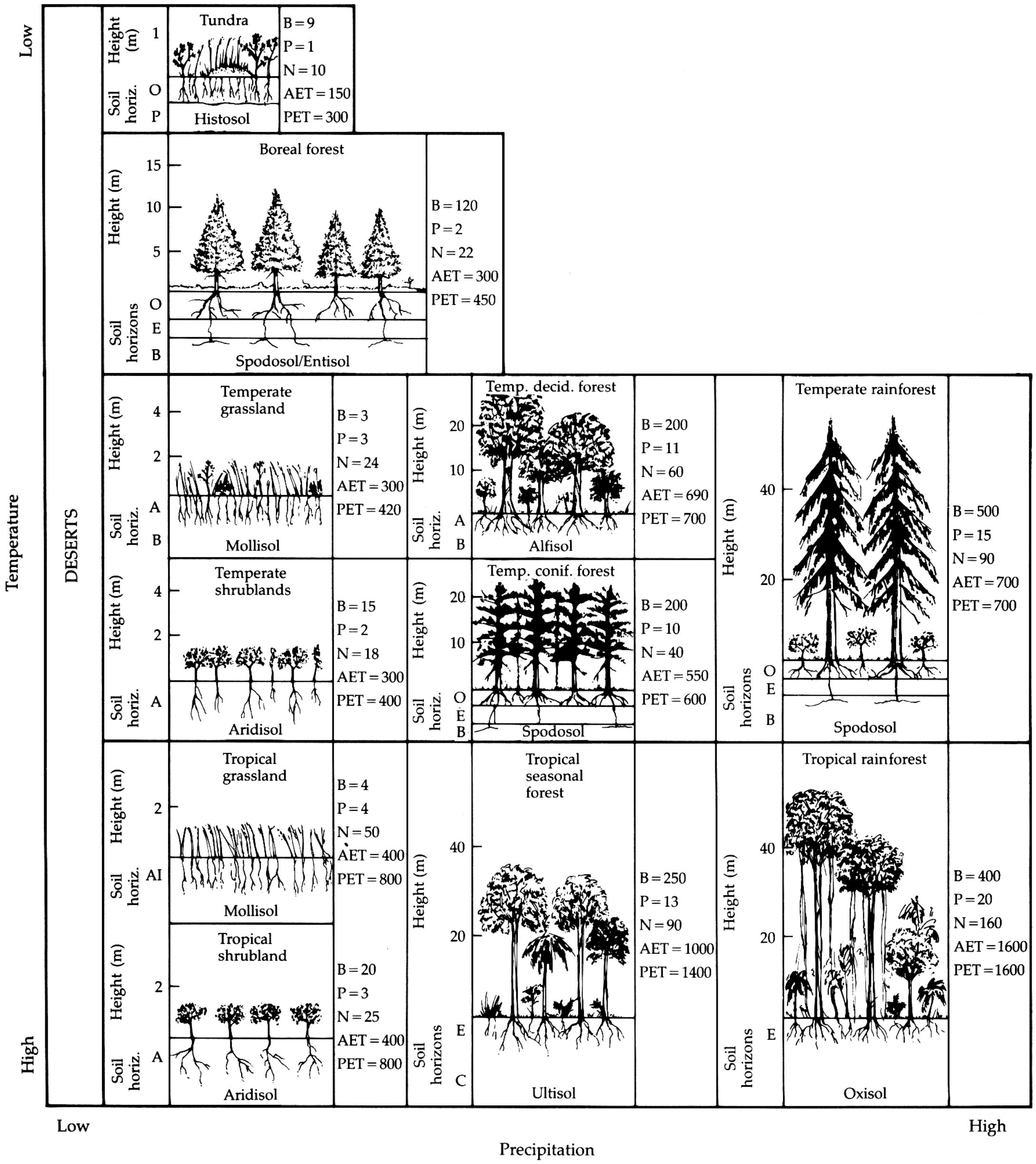


Figure 4. The world's major terrestrial biomes, including their predominant soil type, stature (height of dominant vegetation, m), average biomass (B, t/ha), average NPP (P, t/ha/yr), and average nitrogen uptake by vegetation (N, kg N/ha/yr), arrayed against average annual precipitation and temperature. AET and PET are annual averages of actual evapotranspiration (mm) and potential evapotranspiration (maximum AET without water stress effects). The larger the difference between AET and PET, the more arid the environment (from Aber and Melillo 1991).

Table 3. Carbon stored in aboveground vegetation (biomass) and rates of annual carbon accumulated (typical or average value listed first, followed by overall range in parentheses) in aboveground biomass for selected forest biomes. Carbon accumulation is synonymous with aboveground net primary production (ANPP) from the ecological literature.

Forest System	Surface Area[1] ($M\ km^2$)	Biomss[2] (tC/ha)	Carbon Accmumulation[2] Rate (tC/ha/yr)	Risk Factor (0 - 2)	Carbon Value
Boreal	11.2	50 (25–70)	4 (1–7)	1.2	65
Temperate deciduous broadleaf	3.5	100 (75–125)	7 (2–17)	1.1	118
Temperate coniferous[3]	2.4	110 (75–145)	7 (2–12)	1.0	117
Temperate mixed	3.3	100 (75–125)	7 (2–12)	1.0	107
Temperate evergreen broadleaf	3.2	115 (90–140)	8 (4–12)	0.9	111
Tropical evergreen (0–1,000m)	8.5	245 (190–300)	11 (4–18)	1.9	486
Tropical evergreen (1,000–1,500m)	1.8	205 (160–250)	11 (4–18)	2.0	432
Tropical evergreen (1,500+)	1.5	160 (120–200)	11 (4–18)	2.1	359
Tropical deciduous	5.5	83 (50–125)	6 (2–10)	2.3	205
Plantations (incl. woodlots)[4]	0.13	65 (30–100)	12 (4–20)	0.7	54
Agroforestry and homegardens		30 (10–50)	5.5 (1–10)	0.9	32
Urban forests		25 (10–40)	5 (1–9)	1.5	45

[1]These figures were compiled from a variety of sources and represent best estimates for these forest types (WGBU 1998). FAO (1999) figures are generally lower. Tropical evergreen forests are subdivided into three types based on elevation.

[2]Data were obtained from WGBU (1998), Brown and Gillespie (1989), Spetich and Parker (1992), Goulden et al. (1996), Singh et al. (1994), Rutkowski and Stottlemeyer (1993), Winjum and Schroeder (1995) and Nowak (in press).

[3]Excludes rain forests of the Pacific Northwest region of North America. Biomass carbon values for these forests are the highest in the world, greatly exceeding the maximum values in this table.

[4] Includes a wide range of plantation types and conditions: both short- and long-rotation systems in temperate and tropical zones, and some stands with intensive cultural treatments (e.g., fertilization, weed control, thinnings).

average value. The range is also included to demonstrate the great variability associated with each and highlights the importance of using reliable information when locally available.

The “global risk factors” associated with Table 3 are based on global trends within the forest biomes/systems listed. The greater the risk to a forest system from such events as deforestation, land conversion, uncontrolled harvesting and fires, the greater the number is above 1.0. A rating of 1.0 indicates that that particular system is basically stable. Any value below 1.0 indicates that the forest type is expanding.

The risk factors were developed by the authors based on review of the literature related to the status of the world’s predominant forest biomes/systems. The risk factors reflect the relative status and integrity of major biomes/systems as a result of anthropogenic influence. They are especially relevant for forest biomes under threat from severe fragmentation, degradation or elimination. The overall carbon value is either increased or decreased depending on the relative degree of threat. There is a degree of subjectivity involved in setting these factors and the values should be reevaluated and adjusted over time as the status of particular forest types changes. The methodology for deriving the risk factor is described in Appendix 8.

The carbon value is the sum of the existing carbon in biomass (expressed as tons of carbon per hectare; tC/ha) and accumulation rate (tons of carbon per hectare per year; tC/ha/yr), multiplied by the risk factor associated with that biome/system. Using average values, the highest carbon value possible is 486 (found in lowland tropical evergreen forests) and the lowest is 32 (agroforestry and homegardens). The lowest possible natural forest system is 65 (for boreal forests). It is recommended that mission programs use the average values when no data are available for the forest system in question. Furthermore, when forests have been degraded by selective cutting or land clearing, biomass carbon is reduced depending on the severity of the degradation. Reliable local estimates of disturbance or degradation should be used for all cases and factored into the final carbon value estimate.

The forest system categories shown in Table 3 are very broad, demonstrating significant variation within and among the systems. As indicated above, the average values for tropical lowland and boreal forests are 486 and 65, respectively, thus the carbon value for the most highly productive tropical evergreen forest system is more than 19 times greater than that of the least productive boreal forest system. If the average values are used, the difference is just over 7 times. The carbon values of some of the other systems (plantations, agroforests, urban forests) are only 5% of those of the most productive tropical forests. It should be noted that when the same criteria are used, even the lowest carbon values for forest systems are considerably higher than those estimated for non-forest systems.

Table 3 can assist missions in completing a rapid carbon assessment of their programs at institutional and field levels. Institutional support could include mission work that indirectly affects forest systems through policy development, training programs, endowment development and non-project assistance. A series of examples below help illustrate carbon assessment at the various levels.

Example 1*:* A mission in southern Africa is training personnel working within the Ministry of Forests to implement a program encouraging community management of Miombo (*Brachystegia sp*., tropical deciduous forest) woodlands. Existing studies indicate that the average amount of carbon stored in aboveground biomass of Miombo woodlands is 90 tC/ha and the average rate of accumulation 8 tC/ha/yr. From Table 3, the carbon storage value and accumulation values are added (98) and then multiplied by the risk factor 2.3 to obtain a carbon value of 225. The main objective of related mission activity is institutional capacity building. However, the underlying assumption is that this investment will eventually be directly translated to on-the-ground sustainable management. For that reason, the mission could report that the possibilities to conserve a forest system with a carbon value of 225 have been increased as a result of the training.

Example 2*:* A mission in Southeast Asia supports an endowment for a protected area in a tropical lowland evergreen forest. The endowment was created to ensure a flow of funds for management and research of the protected area. Local studies indicated that on average these forests contain 275 tC/ha in aboveground biomass, with an annual accumulation rate of 4 tC/ha/yr. The final carbon value of that protected area is 531. Although the endowment was established to better manage the protected area, it is not directly carrying out the work. Rather, the endowment is creating more favorable conditions for the work to be satisfactorily completed. In this example, the mission could report that a forest system with a carbon value of 531 is likely to be better managed as a result of this process.

Many field projects supported by USAID have a number of integrated components that deal with the management of natural systems as well as other sites. At the field level, a mission could use this guide and Table 3 to determine a project-level forest carbon value (PFCV), which would provide the mission with an average carbon value for the overall project area. In contrast to the institutional carbon value analysis, the mission would use this value where its program was directly supporting on-ground forest-based activities.

The first step in determining a PFCV would be to stratify the project intervention area according to Table 3. Then the relative carbon value of each area would be calculated and adjusted by the percentage of land area covered by each system. Finally, the values would be summed to provide the total PFCV.

Example 3*:* A mission funds an integrated conservation and development project (ICDP) in Africa that is managed by an international NGO in association with a host country's natural resource management agency. The project focuses on the conservation of a low- to mid-altitude tropical evergreen forest, with a total area of 100,000 ha. Ground activities concentrate on improved forest protection and work with surrounding communities to promote agroforestry systems and create village woodlots. The project area also encompasses two medium-sized towns. The total project intervention zone is 250 km^2 or 250,000 ha, including the protected area.

The project zone is divided in the following manner: low-altitude evergreen tropical forest = 60,000 ha, mid-altitude forest = 40,000 ha, agroforests = 110,000 ha, village woodlots = 10,000 ha and urban zones = 40,000 ha. Biomass and accumulation rates are known only for the forests and the woodlots. For the low-altitude forest, the biomass is 230 tC/ha, with an accumulation rate of 7 tC/ha/yr. The figures for the mid-altitude forest are 215 tC/ha for storage and 6 tC/ha/yr for accumulation. The woodlots have been recently established, and figures were obtained from other well-established woodlots in the area using the same species and seed sources. The storage figure is 20 tC/ha and the sequestration rate is 12 tC/ha/yr. Average values are used for both the agroforestry and urban forestry systems from Table 3. Carbon values for each forest system are calculated by using Table 3 and then adjusted by the percentage of total land covered by that forest system. For this example a program balance would look like the following:

Forest System	**Biomass**	**Accumul.**	**Risk Factor**	**C Value**	**Area**	**Adj. C Value**
Low-altitude forest	230	7	1.9	450	.24	108
Mid-altitude forest	215	6	2.0	442	.16	71
Agroforestry	30	5.5	0.9	32	.40	13
Plantation (woodlots)	20	12	0.7	22	.04	1
Urban forestry	25	5	1.5	45	.16	7
Total Project Forest Carbon Value						200

The total PFCV is the sum of the adjusted carbon (C) values which, in this case is 207. The same data could also provide the average project carbon storage per hectare and the average carbon accumulation rates.

Example 4: This example involves a South American mission supporting a government/ private sector/NGO consortium that develops fast-growing *Eucalyptus* plantations on degraded agricultural land for biomass production. The project includes efforts to get local people to practice more intensive agroforestry and to develop their own community eucalyptus plantations, the wood from which will eventually be purchased by the consortium for energy. The communities are being encouraged through training and distribution of educational materials to protect the remaining natural tropical deciduous forests in the area, which have been seriously degraded. The project is working with schools in the project zone to promote conservation education through urban tree planting.

The project intervention zone covers a total area of 6,000 km^2. Within this zone, plantations are to be established on 400 km^2 of land; agroforestry promotion is on 3,200 km^2, community woodlots on 100 km^2. The remaining natural forests comprise 2,000 km^2 and urban areas account for 300 km^2. For the plantations and woodlots, during a commercial rotation of 6 years, the average total carbon storage capacity is estimated at 80 tC/ha, with a mean annual increment of 18 tC/ha/yr. The natural forests are productive when protected, but the standing carbon has been reduced by 30% owing to degradation. The storage value is obtained from previous inventories as 100 tC/ha (70 tC/ha when adjusted for 30% degradation), with an accumulation rate of 9 tC/ha/yr. The improved agroforestry systems have an average storage of 35 tC/ha and a sequestration rate of 7 tC/ha/yr. Average rates from the table are used for the urban planting. The project forest carbon value is then calculated as follows:

Forest System	Biomass	Accumul.	Risk Factor	C Value	Area	Adj. C Value
Plantations	80	18	0.7	69	.07	5
Tropical deciduous	70	9	2.3	182	.33	60
Agroforestry	35	7	0.9	38	.53	20
Community woodlots	80	18	0.7	69	.02	1
Urban forests	25	5	1.5	45	.05	2
Total Project Forest Carbon Value						88

If the project is implemented as planned, the actual project carbon value will eventually be higher, as the use of eucalyptus for biomass energy will offset a certain level of fossil-fuel use. If and when that information becomes available, it can be incorporated into the decision-making process to help determine the viability and utility of the project.

This example raises other points regarding carbon values and forest systems. First, it is clear in this scheme that natural forest systems have the greatest carbon values, and that their conservation will likely continue to be a priority, not only for biodiversity, watershed management and soil conservation, but for carbon management as well. Second, as mentioned above, this approach only addresses carbon in aboveground forest biomass. Most terrestrial carbon is actually found in soils. And as also indicated earlier, soil carbon, at least the humic substances in soil organic matter, is considerably less reactive than aboveground forest carbon and is more technically difficult to manipulate and manage, compared with aboveground vegetation. A third, and related, point is that carbon storage in the vegetation of agriculture, grasslands and other non-tree land covers is very low compared with that of any tree-based system. However, improved management of these systems can contribute to enhancing soil carbon, at least through reduced erosion and runoff.

It is recognized that USAID missions are limited in the amount of time and resources they can directly allocate to the monitoring of carbon changes in various forests. They are well positioned, however, to help initiate carbon-monitoring activities within other organizations and to support ongoing initiatives designed to do similar work. From an institutional perspective, most mission E/NR programs work with contractors, NGOs, universities, host-country agencies and the private sector. These collaborating partners and institutions could be provided a grant or contract to carry out the work on a national survey, for example. For ongoing or planned activities within a mission, existing agreements with contractors or NGOs could be renegotiated and modified to include the project-level carbon-value work outlined above.

Once an agreement is made with an institution or organization involved in forest management, a mission can simply request information as part of its regular reporting requirements about practices related to carbon. In most cases, this information is already being collected as part of other ongoing monitoring work (biodiversity conservation projects, watershed and soil conservation initiatives, sustainable forest management work, agroforestry production and so forth). Examples of such information include deforestation rates in protected areas (by forest type and area), harvest intensities in production forests (by volume, type and area), reforestation and afforestation (by type and area), agroforestry plantings (species and area) and urban plantings (by species and area). If ongoing activities supported by the mission are not recording this type of information, the Climate Change Initiative provides a good opportunity to encourage them to begin doing so.

To take this initiative one step further, a system of permanent inventory plots, or the rehabilitation of older ones, could be included. This could be carried out in close collaboration with appropriate government or private agencies and would serve several purposes. The plots would allow regular monitoring of biomass, growth (from which biomass accumulation rates can be estimated), species diversity and disturbance patterns. Most countries already have a system of permanent forest inventory plots; a mission could determine how best to build on such a system, particularly in relation to mission activities already taking place. Agroforestry systems and urban plantings are less likely to have permanent inventory plots, but plots could be installed in association with other ongoing research.

Appendix 1 Carbon as an Element: Its Properties and Forms

Carbon is a nonmetallic element with an atomic weight of 12. Its elemental number (atomic number) is 6, which puts it between boron (5) and nitrogen (7) in the Periodic Table of Elements. The inner level of electrons, or K shell, for carbon is filled (two electrons). The next layer, or L shell, could hold up to eight electrons. Carbon has only four electrons in this shell, giving it a unique ability to form strong bonds with itself as well as with other elements (Brown 1989). This property allows it to bond with other compounds in nature, which is critical for the existence of life.

Carbon has four known isotopes: ^{11}C, ^{12}C, ^{13}C and ^{14}C. ^{12}C and ^{13}C are known as the "stable isotopes," with ^{12}C found much more commonly in nature (98.9% and 1.1%, respectively; Edwards and Marsh 1989). The radioactive isotope, ^{14}C, is generated in the upper atmosphere by the neutron bombardment of nitrogen. It is very useful as a tracer in the study of organic reactions and ecological processes, and for dating archeological artifacts (Coleman and Fry 1991). The ^{11}C isotope is comparatively short-lived, with a half-life of 20.4 minutes as opposed to a half-life of 5,770 years for ^{14}C. It is a valuable radioactive tracer used, for example, in plant physiological studies that would difficult or impossible using ^{14}C or other isotopes (Spence and Sharpe 1991).

Elemental carbon has several basic structures that are found in different forms in the earth's crust. The first and most widespread structure is graphite, consisting of two-dimensional hexagonal layers. Another, and very rare form, is diamond, a three-dimensional network that is very rigid and stable (the hardest natural material known). Carbon is also found as Fullerite solids, geodesic structures of cage-like spheroids having five-membered rings (pentagons) and some six-membered rings (hexagons); carbynes, which are long chains having double or triple bonds; and noncrystaline materials (Henning and Salama 1998).

Nongraphitic forms of molecular carbon are derived mainly through the process of carbonization. Carbonization is the formation of materials with increasing carbon contents from organic material, usually by pyrolysis (chemical change brought about by heat). Forms of graphitic carbon include "pitch," oil, coke, coal, carbon fiber and various composites. Nongraphitic carbon molecules include cellulose in wood, nut-shells (husks) and nonfusing coals (Edwards and Marsh 1989).

Another form of inorganic carbon, which is among the most widely distributed minerals in the earth's crust, is the carbonate mineral ion, CO_3^{-2}. The elements that most commonly bond with the carbonate ion are calcium, sodium, iron, uranium, aluminum and manganese. The most abundant and well-known carbonate minerals include calcite, dolomite and argonite. Calcite is a primary constituent of rocks like limestone and marble.

Some of the carbonate minerals, particularly calcium carbonate, are associated with the more arid regions of the world. Carbonate accumulation occurs during dry periods when evaporation of groundwater causes precipitation of dissolved solids in the upper soil layer. This addition of carbonates to the soil profile greatly increases its alkalinity. In large parts of the southwestern United States and northern Mexico this buildup of calcium carbonate in the soil profile develops a hard, almost impervious layer known as caliche. The manufacture of cement utilizes calcium carbonate, liberating CO_2 as a by-product, which constitutes a significant contribution to the buildup of atmospheric CO_2.

The ability of carbon to bond with nitrogen, oxygen, hydrogen and other elements has been the focus of most of the research conducted on carbon. In fact, one entire branch of chemistry, organic chemistry, is dedicated to carbon and its compounds. Although the term organic brings to mind compounds that are either of plant or animal origin, the range of organic chemistry is considerably wider. In addition to studying, for example, natural medicines and textiles, organic chemistry focuses on human-made products such as sulfa drugs, nylon, rayon, Teflon®, Styrofoam®, polyethylene and other polymers used to manufacture films and plastics (Brown 1989).

Appendix 2 Carbon in Nature, Its Global Cycle, and Its Role in Photosynthesis and Respiration

Carbon is found throughout the universe, fourth in abundance among the elements following helium, hydrogen and oxygen (Figure 5). As stars evolve and cool, matter is released into interspace, with the concentration of elements in it approximating the order

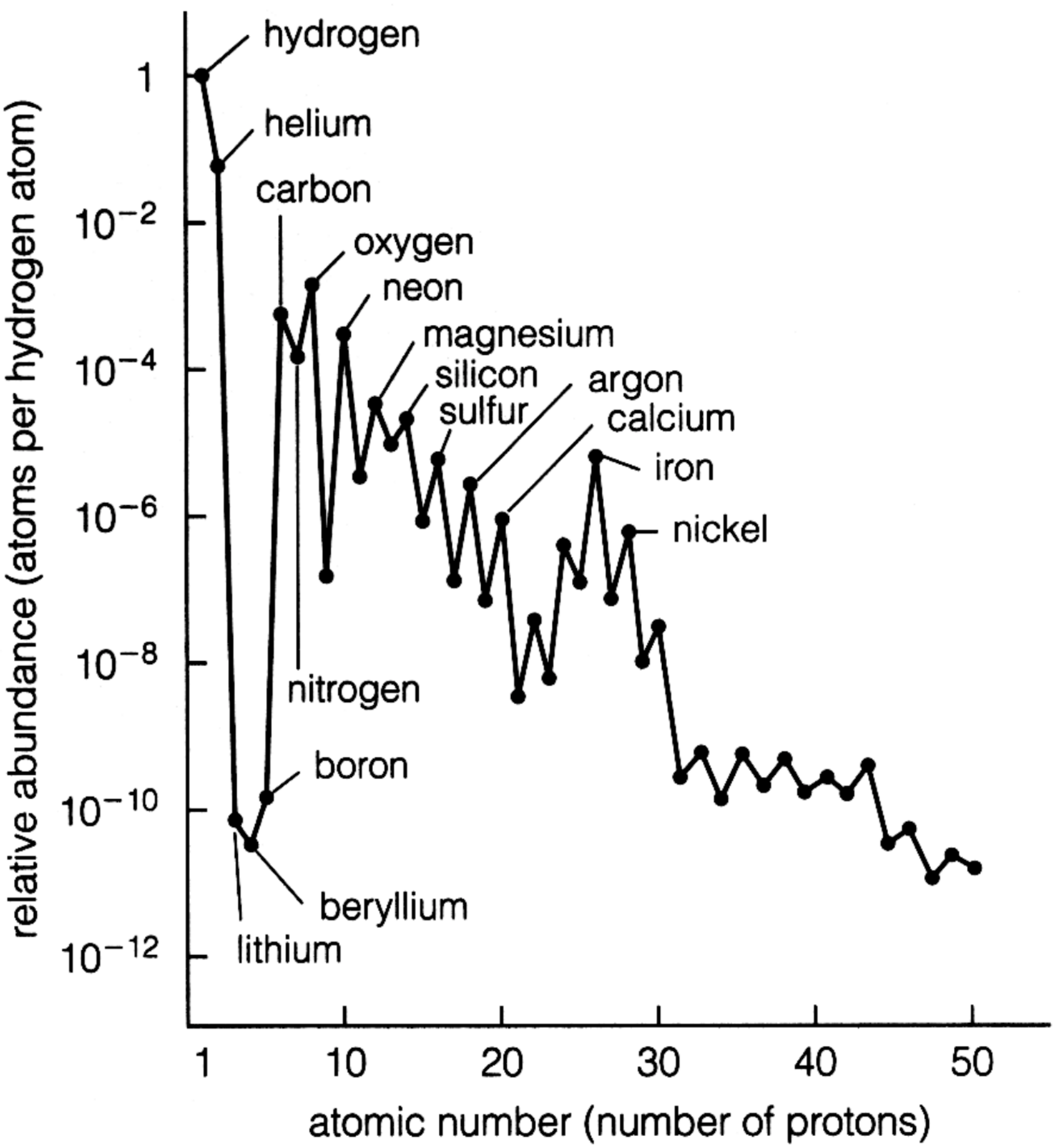


Figure 5. The relative abundances of elements in the universe (after Goldschmidt 1938).

shown in Figure 5. This suggests that outer space is relatively rich in carbon, nitrogen, hydrogen and oxygen. Investigation of some interstellar molecular clouds suggests the presence of a number of organic compounds, which has led some scientists to speculate recently that life on earth actually originated elsewhere (Henning and Salama 1998).

The more conventional theory, however, is that life originated on earth as the result of chemical processes acting on basic organic compounds. Within this context, it is worth noting that carbon is found in even greater relative abundance to hydrogen on earth than in space. This greater abundance may be largely attributed to the high carbon requirements for maintaining the biosphere.

The global pool of carbon is estimated at about 42,460 billion metric tons (or gigatons, Gt). Of this, 39,200 Gt C is found in the oceans, 2,000 Gt C in the soil (including roots), 760 Gt C in the atmosphere and 500 Gt C in aboveground biomass (Watson 2000). Changes in the pools of carbon are accompanied by fluxes of CO_2 (Figure 6), many of which are very difficult to measure or estimate. The numbers in Figure 6 represent a best-estimate “snapshot” of the global carbon cycle for 1996. The budget for any given year could look slightly different than what is presented here.

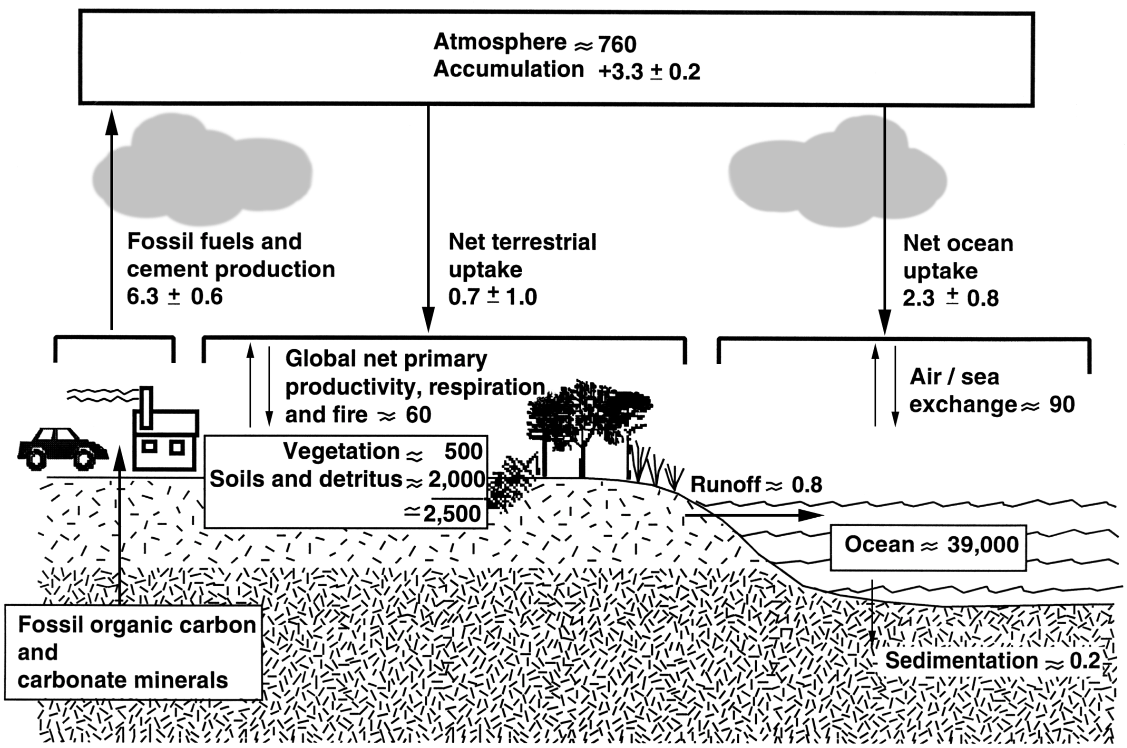


Figure. 6. The global carbon cycle, showing the average annual reservoirs (Gt C) and flows (Gt C/yr) relevant to human-caused changes from 1989-1998 (from Watson et al. 2000).

New carbon enters the global cycle in one of two ways. The first is through the upper atmosphere, where radioactive isotopes ^{14}C and ^{12}C are created from bombardment of atmospheric nitrogen by solar radiation. The second is from the lithosphere to the atmosphere through volcanism and metamorphism during which CO_2 is released. Both of these inputs of carbon to the global cycle are minute compared with natural fluxes and those now occurring owing to human activities (Tans and White 1998).

Carbon dioxide (CO_2) is much more abundant in the hydrosphere than in the atmosphere, unlike all other gases on earth. Carbon dioxide enters the oceans either through plant photosynthesis (by phytoplankton) or by simple diffusion. Carbon enters the biosphere through photosynthesis and, as animals eat plants, the carbon becomes distributed. Carbon then reenters the atmosphere from the biosphere through the respiration of plants, animals and decomposer organisms, mainly microbes. Carbon enters the lithosphere via the hydrosphere through the secretion of calcium carbonate by marine organisms (forming limestone).

For millions of years, large fluctuations have occurred in the amounts of carbon circulating among the pools in the natural carbon cycle, in conjunction with the evolution of the earth and the development of vegetation and the principal water and ice bodies. Once CO_2 enters the atmosphere, it moves freely among the other reservoirs, and atmospheric CO_2 balances change in the oceans and on land. The residence time of carbon (C) in the atmosphere is very short, when compared with turnover times in the biosphere, hydrosphere and lithosphere. The residence time for a CO_2 molecule in the atmosphere is only a few years, while turnover times in the oceans and biosphere are measured in decades to centuries.

The energy for all biological processes on earth comes ultimately from the sun. On the earth's surface, solar energy is absorbed by chlorophyll pigments in plants during photosynthesis and the absorbed energy is used to split CO_2 from the atmosphere into its constituent atoms in leaves. Photosynthesis follows the general reaction:

$$nCO_2 + H_2O + \text{light} \;=\; (CH_2O)_n + O_2$$

where n is a whole number. The assimilation of carbon involves chemical reactions that occur in chloroplasts within the leaf mesophyll cells, catalyzed by numerous enzymes. The fixed carbon is then combined with oxygen and hydrogen from soil water to form more complex carbohydrates (actually $< 2\%$ of the sun's energy is used in photosynthesis; the rest is used to evaporate water or is converted into heat). The simplest carbohydrate formed is glucose ($n = 6$), which leads to the formation of more complex compounds, such as proteins, lignin, cellulose and amino acids, or storage forms such as starch. Oxygen (O) is the other important by-product of photosynthesis.

Respiration is essentially the reverse of photosynthesis and involves oxidation of organic compounds producing CO_2, water (H_2O) and the energy needed for growth and maintenance of living tissues. There are two sources of respiratory carbon. Heterotrophic respiration is the oxidation of dead organic material in the soil or on the forest floor (also known as decomposition), as well as respiration of insects, animals and other microbes. Autotrophic respiration is that of plant tissues (e.g., leaves, stem sapwood, roots, fruits). A portion of the energy from respiration is used to generate adenosine triphosphate (ATP), a carrier of energy within plants that is then used for growth, maintenance or reproduction. The rest of the energy is released as heat.

In relation to carbon assimilation during photosynthesis, most plants belong to one of two groups. Most are known as C3 plants, because the primary product of photosynthesis is a three-carbon sugar. Less common are C4 plants, which nevertheless include some of the tropical grasses, including maize and sugarcane. C4 plants produce a four-carbon compound as the primary product of photosynthesis and have a lower concentration of CO_2 inside the stomata of leaves, which results in higher photosynthetic rates and higher water-use efficiencies (Campbell and Norman 1998). Aboveground biomass and water-use efficiencies for C3 plants appear to increase linearly with elevated CO_2 concentrations (Polley et al. 1993), which must be taken into account when modeling the global carbon cycle.

Appendix 3. The Greenhouse Effect

Though the greenhouse effect has attracted a great deal of attention in recent years in relation to global warming, its role as a natural process that is primarily responsible for allowing life to flourish only on earth in our solar system is often overlooked. The greenhouse effect results from the capture of re-radiated heat (generated by the absorption of solar radiation by the earth's surfaces) by atmospheric gases (CO_2 in particular, but also water vapor H_2O, nitrous oxide (N_2O) and methane (CH_4)) near the earth's surface (Figure 7). This insulating effect maintains higher (by about 18°C) and more stable surface temperatures than would otherwise occur.

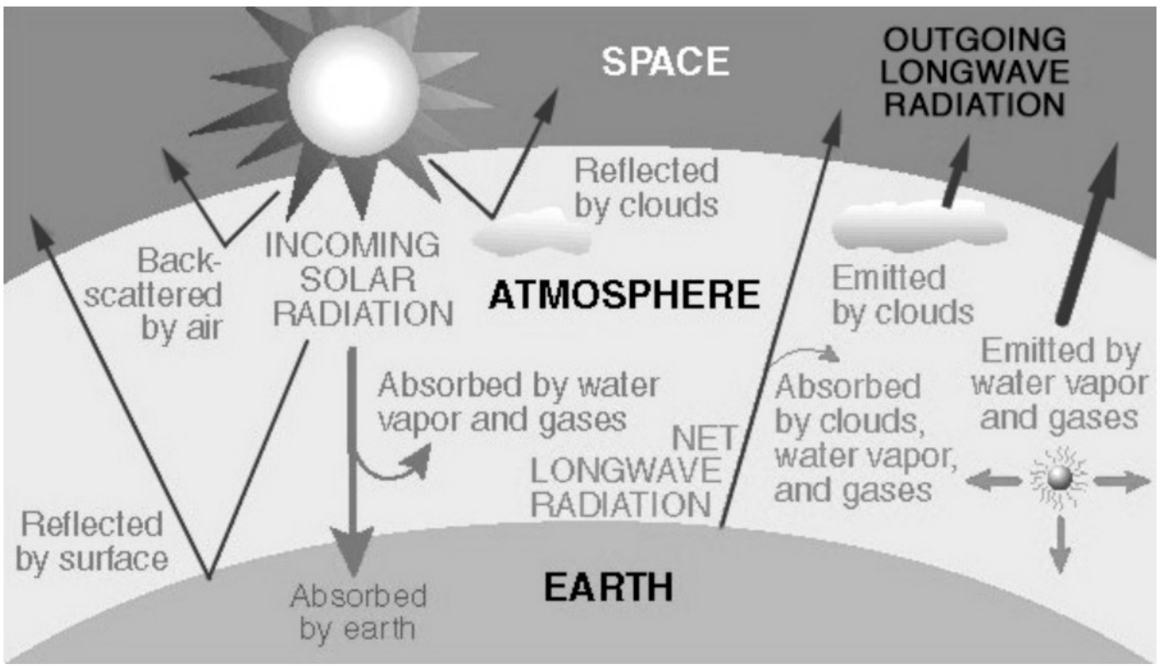


Figure 7. A conceptual model of the energy balance of the earth.

More specifically, about 99.998% of the energy entering the earth's atmosphere comes from solar radiation (geothermal energy from the earth's interior makes up the other 0.002%). The sun radiates energy at extremely high temperatures (6,000 Kelvin) and short wavelengths (less than 3.5 microns). A full 30% of the solar radiation that reaches the top of the earth's atmosphere is reflected back to space by particulate matter in the air, clouds and the earth's surface. This reflectance of solar radiation by a surface is termed its albedo (i.e., the earth's albedo is about 0.3). Of the 70% that is not reflected, about 25% is absorbed by the atmosphere (by water vapor, dust, clouds and atmospheric gases, including absorption of harmful ultraviolet radiation by ozone (O_3)), and is eventually reradiated back to space as heat. The balance of 45% is absorbed by the surface of the earth.

The earth reradiates energy at much lower temperatures than does the sun (about 270 Kelvin), which also means in longer wavelengths (greater than 3.5 microns). The balance of the 45% energy absorbed is eventually lost as heat to space, thus balancing the earth's energy budget. However, the surface-absorbed energy is not all reradiated as heat to the atmosphere. In fact, there are two very different forms of energy released to the atmosphere: latent heat and sensible heat. Latent heat transfer refers to the energy released through the transformation of water from liquid or solid forms into water vapor (a gas). In the case of the earth's surface, most of the absorbed energy is used to evaporate water. As the water vapor that is evaporated or transpired (i.e., taken up from the soil and evaporated from inside plant leaves through stomata to the atmosphere) from the earth's surface rises, it cools and eventually condenses, thereby releasing its latent heat energy into the atmosphere. Sensible heat transfer is the energy released as heat that we can feel, and is actually a relatively minor component of the surface energy balance.

Data indicate that atmospheric CO_2 is at much higher levels now than during the past several hundred thousand years, with the rate of increase during the twentieth century unprecedented (Tans and White 1998). The net increase in atmospheric CO_2 is projected to continue well into the twenty-first century. The implications are that we will have to deal with an increasing greenhouse effect and any associated changes in climate, will have to more intensively manage our global carbon pools, or both.

A great deal of policy attention and scientific focus have been placed on understanding this phenomenon, since the rapid buildup of CO_2 in the atmosphere is most directly responsible for any global warming that occurs (CO_2 has a much higher atmospheric concentration than do other greenhouse gases). Concentrations of CO_2 in the atmosphere since the mid-1800s are highly correlated with fossil-fuel emissions (Figure 8).

In pre-industrial times, the amount of CO_2 in the atmosphere changed only gradually as a result of natural processes not entirely understood today. However, since the middle of the nineteenth century, the amount of CO_2 in the atmosphere has increased by about 30%. Most of this increase, as much as 70%, has been attributed to the use of fossil fuels for energy (during which carbon in reduced form in organic matter is oxidized to CO_2; Houghton 1996). If the same amount of fossil fuel is used to generate energy through combustion engines in the future as occurs now, this trend will continue. It is worth noting that, even if fossil-fuel emissions were stabilized immediately, CO_2 would continue to build up in the atmosphere well into the twenty-first century.

Although scientific evidence clearly demonstrates that humans are exacerbating the greenhouse effect, scientists are still working to gain a more complete understanding of the global carbon budget so that human-induced changes and likely future climate conditions can be more accurately assessed. For example, some still argue that post-industrial changes in temperature are due mostly to natural, not human-caused processes (i.e., variation in the energy output of the sun; Friis-Christensen and Lassen 1991). Reconciling these differences and arriving at a common understanding will continue to be a global research priority for the foreseeable future.

Appendix 4. Anthropogenic Sources of Atmospheric Carbon: Balancing the Global Carbon Cycle?

1. Fossil-Fuel Combustion

Since the mid-nineteenth century, sources of energy have changed dramatically. In 1860, wood was the primary fuel used throughout the world. Wood was gradually replaced by coal as the number one energy source near the end of the 1800s, and coal remained the number one source in industrialized countries until around 1960. Since that time, coal has been replaced at the top position by oil (Nakicenovic 1996). The use of natural gas and hydroelectric power has also increased significantly during the past 50 years.

Most of the consumption, as well as the changes in relative sources used, have taken place in the more industrially developed countries (Figure 8). As of 1990, 25% of the world's population consumed 80% of the energy used. From a geographical standpoint, the greatest contrast in energy consumption is between North America and Africa, the former consuming 20 times more energy than the latter on a per capita basis (Nakicenovic 1996). On a country-to-country basis, the differences can be far greater.

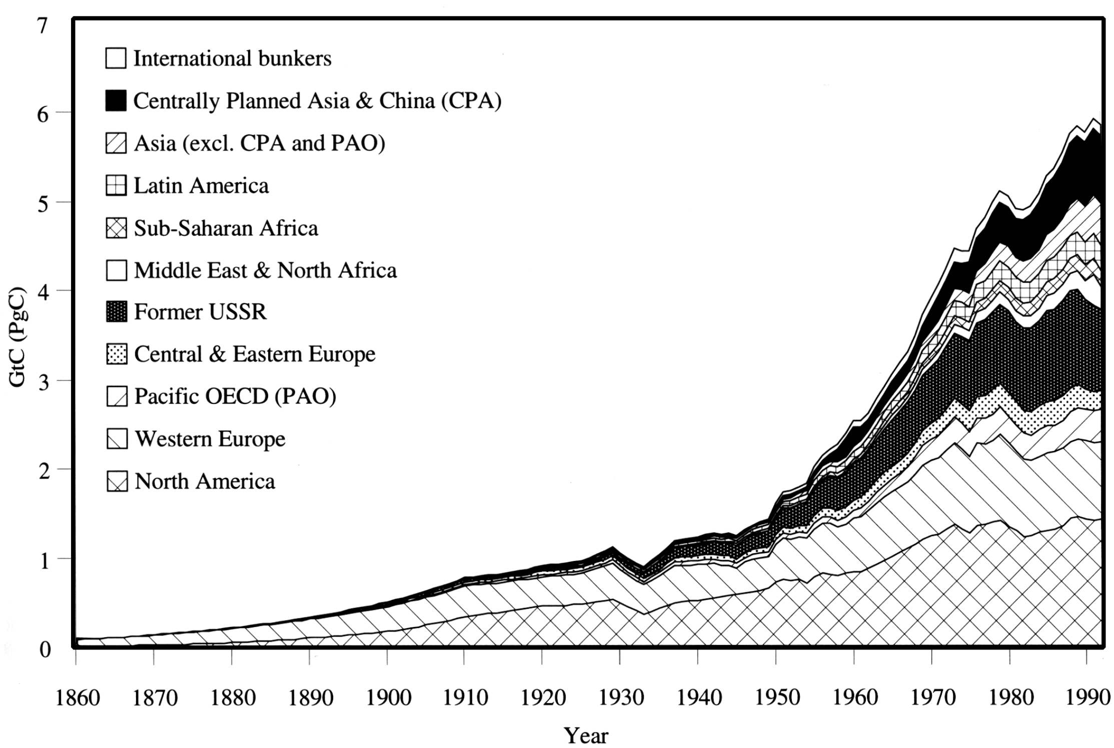


Figure 8. Estimated annual global emissions of carbon (in Pg) for various regions of the world, from 1860-1992 (from Watson et al. 1996).

Since 1850, about 265 Gt C have entered the atmosphere from fossil-fuel use and cement production (Watson 2000). Recent estimates place global fossil-fuel CO_2 emissions at about 6.3 Gt C/yr (Marland et al. 1999), with the United States alone contributing about 1.4 Gt/yr. Annual natural CO_2 emissions (from respiration) are estimated to be about 100 Gt C per year, which means that fossil fuels comprise only about 6% of the total. However, the reverse process of photosynthesis consumes about the same amount during respiration, so that the net difference between the two opposing natural fluxes is very small (Houghton 1995).

2. Land-Use Change

Increases in atmospheric CO_2 will continue to come primarily from the use of fossil fuels for the foreseeable future. However, approximately 30% of the CO_2 emissions since the mid-nineteenth century have resulted from changes in land use (Figure 9).

The key land-use change has been the conversion of forests into agriculture or pasture. This activity has had a major impact on CO_2 levels because much of the carbon stored in trees and dead organic matter (detritus) in forests is released to the atmosphere when forests are cleared and cultivated. Some of the release from stored vegetation carbon occurs rapidly through burning, with the rest released more gradually through decomposition or burning of residues and forest products. As the world's population continues to increase, a considerable amount of forestland is being converted into urban uses to support this burgeoning population.

Studies conducted by Houghton (1996) show that between 1850 and 1990, about 100 Gt of carbon were released to the atmosphere as a direct result of land-use change at a global scale. More recent estimates indicate the total C released to the atmosphere since 1850 is now at 124 Gt C, an increase of 24 Gt C during the past decade (Watson 2000). The rate has increased on an annual basis, with the amount of carbon released equaling approximately 1.6 Gt/yr by the late 1980s. It is estimated that tropical deforestation contributes about 1 Gt/yr of this, or just over 60% of the overall anthropogenic emission rate (IGBP 1998).

3. Is there a "Missing Sink"?

Of the 7.9 Gt of carbon released annually from human activities, about 6.3 Gt comes from fossil-fuel emissions and 1.6 Gt from land-use changes. The oceans take up about 2.3 Gt of this, the atmospheric increase is about 3.3 Gt, and regrowth of Northern Hemisphere forests can account for about 0.5 Gt. Where does the remaining 1.3 Gt go? This amount has been referred to as the "missing sink" in the global carbon cycle.

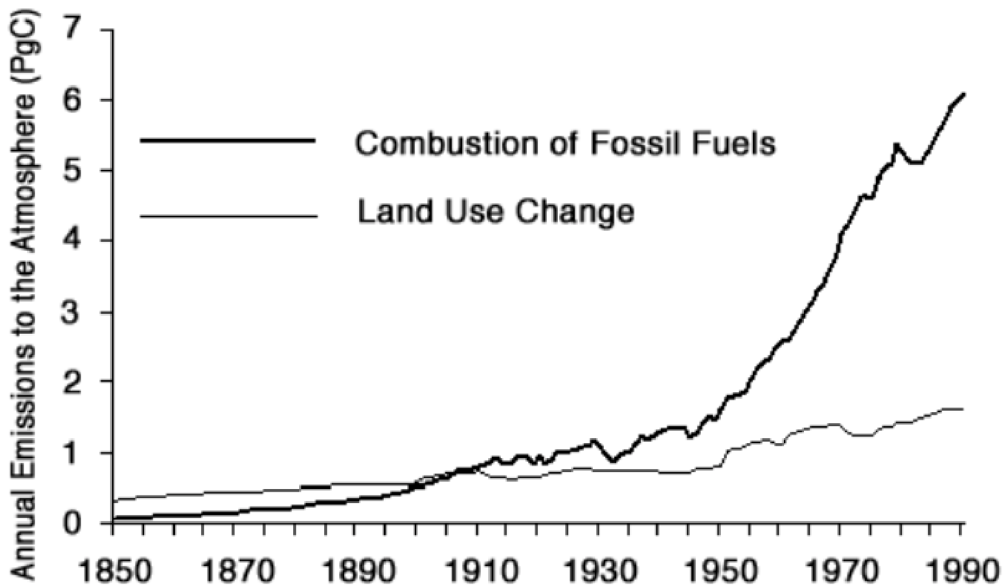


Figure 9. Estimated annual global emissions of carbon to the atmosphere from two different sources: fossil fuel combustion and land-use change, from 1850 to 1992 (from Watson et al. 1996).

Although such a conclusion is far from certain at this time, measurements of the carbon and oxygen isotopic composition of the atmosphere indicate that the so-called missing sink may well be in existing forests of the mid-latitudes of North America, Europe and Asia (Ciais et al. 1995). This could occur as a result of "CO_2 fertilization," the stimulation of photosynthesis by elevated atmospheric CO_2 concentrations. One report even suggested that U.S. forests alone could constitute the unknown sink (Fan et al. 1998). Other factors could also be at work. Some argue that the sink could actually be in remaining natural tropical forests (Grace et al. 1995), regrowing areas of the tropics no longer classified as forests (Houghton et al. 2000), or that the uncertainties involved preclude any judgment as to whether a missing sink even exists. Disagreements have shifted the recent research focus to obtain better estimates of carbon dynamics at regional and smaller scales, since it is easier to model and monitor the climate system at these levels than to assess the entire globe at once (Tans and White 1998).

Appendix 5   Status of Global Forest Resources

1.   Major Forest Biomes

The world's forest biomes cover an area of approximately 41 million (M) km^2 (or 4.1 billion hectares (ha)). The majority of these forests (43%) are in the tropics. The rest are found in temperate regions (30%) and the boreal zone (27%; Iremonger et. al 1997; WGBU 1998; FAO 1999).

In total, the world's forests contain 1,146 Gt C, with 359 Gt in vegetation and 787 Gt in soils. More than half of the soil carbon is found in boreal forests (471 Gt C), while two-thirds of the vegetative carbon is in tropical forests (212 Gt; WGBU 1998).

The forest biomes in this report are taken from the vegetation classification system of Aber and Melillo (1991). This was selected as a middle-of-the-road system in terms of complexity. The biomes were defined based on two broad criteria: major climatic zones (boreal, temperate and tropical) and physiognomy of the vegetation (broad-leaved vs. needle-leaved, deciduous vs. evergreen). Other names commonly associated with these biomes are given in parentheses following the names of the biomes below.

<u>Boreal Forests (subarctic/subalpine forests, taiga, northern coniferous forests).</u> Boreal forests, in one form or another, have existed since the mid-Cretaceous period. Their range expands to the south during glacial periods and retreats northward during interglacial times. Boreal forests (except for some subalpine forests) are restricted to the Northern Hemisphere and cover an area of approximately 11.2M km^2. They are found in two geographic zones, the largest stretching from Western Europe (Scandinavia) to eastern Siberia. The second region is a broad band of forests ranging from eastern Canada and the northeastern United States to British Colombia and north to Alaska. The climate of boreal forests is harsh, the soils generally not well developed and nutrient poor. The terrain has been heavily influenced by Pleistocene glaciation and is characterized by numerous lakes and bogs. Tree species diversity is very limited, with nine dominant species in the North American forests and fourteen in the Euro-Asian forests. Annual productivity is low and, owing to their climate and general inaccessibility, they are among the most poorly managed forest ecosystems in the world. Large and persistent fires are commonly associated with this biome.

<u>Temperate Deciduous Forests (temperate mesophytic forests)</u>. Temperate deciduous forests cover an area of about 3.5M km^2 and are found in areas characterized by year-round soil-moisture retention and a long frost-free summer. They generally occur between 30° and 50° north latitude. Temperate deciduous forests can be found in one small area in the Southern Hemisphere: the southern coastal areas of Chile. The major geographical regions of the temperate deciduous forests are the eastern United States, Europe, the western part of Turkey, the eastern border of Iran, western China and Japan. This biome has a higher diversity than either the temperate coniferous or the boreal forests, the highest diversity found in the United States. It has been extensively altered by human activity, particularly in Europe.

These forests date back to late Eocene times when most of the characteristic genera were growing either intermixed with tropical species at southern latitudes, or were part of a continuous temperate forest belt farther north. Some of the major tree species of this biome (maples *(Acer)*, birches *(Betula)*, hackberries *(Celtis)*, poplars *(Populus)*, cherries *(Prunus)* and oaks *(Quercus)*) are among the more primitive deciduous species, believed to have evolved from tropical ancestors. Many herbs associated with this biome have ligneous tropical relatives. In terms of evolutionary plant geography, this biome reinforces the theory that the stable equatorial forest belt has supplied the temperate zones in both hemispheres with flora that became adapted to frost and then were isolated on either side of the frost-free tropics.

<u>Temperate Coniferous Forests (temperate mesophytic, temperate xerophytic forests).</u> Temperate coniferous forests are mainly located in the Northern Hemisphere and occur over a wide range of climates, perhaps the widest geographic range of any forest biome. This biome covers an area of about 2.4M km^2. Temperate conifers grow on a wide range of soils but tend to dominate drier and less fertile soils that cannot support the nutrient and water demands of deciduous trees. For example, they are found in western North America where hot, dry summers but mild, moist winters favor evergreen conifers. In addition to North America, this biome is found in Europe, China and mountainous areas of Korea, Japan, Mexico, Nicaragua, Guatemala and Chile. Some of the conifers, particularly the pines (*Pinus*), have been extensively planted outside their natural ranges in Southern Hemisphere plantations.

Of particular interest are the continuous coastal-range forests from Prince William Sound, Alaska, to central California. This region contains the most massive natural forests on earth. These characteristics result from high humidity, moderate temperatures controlled by the warm Japanese current, and the relatively slight effects of Pleistocene glaciation (Waring and Franklin 1979).

<u>Temperate Mixed Forests (temperate mesophytic, temperate xerophytic forests)</u>. Temperate mixed forests cover an area of approximately 3.3M km^2. Both deciduous and evergreen species make up these forests found in the eastern United States, Europe, northern Iraq, Iran and China. The climates are similar to those discussed for the temperate deciduous and temperate coniferous forests. The temperate mixed forests consist of species with very different ecophysiological characteristics, which presents forest managers with additional challenges. Less information is available on productivity and management of these forests than for the two related biomes.

<u>Temperate Broad-Leaved Evergreen Forests.</u> Temperate broad-leaved evergreen forests can be further subdivided into several groups based on climatic conditions. One is the schlerophyll forests, associated with a Mediterranean-type climate with wet winters and dry summers. A second includes rain forests of humid, frost-free climates. Still a third is found throughout the coastal regions of the southeastern United States, which have cool, dry winters and moist, hot summers. Schlerophyll forests are found in the western United States, around the Mediterranean, from northern India to southern China and in Australia.

Rain forests are found in Japan, Chile, New Zealand, Australia and some parts of Asia. In all, temperate broad-leaved evergreen forests cover an area of about 3.2M km^2. In the United States and the Mediterranean the dominant species is oak (*Quercus*), in Australia it is *Eucalyptus*, and in other areas it is frequently *Nothofagus*. In all regions where this biome is found, the forests have been extensively harvested or the land has been converted to other uses by humans. This is especially true in the Mediterranean, Australia and New Zealand.

<u>Tropical Evergreen Forests (tropical mesophytic, tropical rain forests).</u> Tropical evergreen forests comprise the single largest forest biome in the world, with an estimated area of up to 12M km^2. This biome is mostly found in three disjunct parts of the world: the Amazon Basin and bordering mountain slopes; the Congo River drainage in west-central Africa (including the highlands of mountainous Rwanda, Burundi and western Uganda); and the Indo-Malaya region, which includes the Malay peninsula and the many islands of the Indonesian archipelago as well as Borneo, Sarawak and Papua New Guinea. Scattered representatives of this biome also occur in Mexico, Central America, western and eastern Africa, northeastern Australia, southeastern India and parts of Sri Lanka.

Tropical evergreen forests have been the most stable of all the forest biomes over the earth's history and have likely existed since the beginning of the Cenozoic era. They contain by far the greatest biodiversity (greatest number of species) per hectare. Precipitation (annual totals and seasonal patterns) is the principal environmental factor affecting forest growth and adaptation. Frost becomes a factor only in alpine areas, and temperature plays a more important role in mountainous areas.

This broad biome contains several subdivisions based mainly on elevation. The largest is that of the lowland rain forests, which are found from sea level up to 1,000 m and cover about 8.5M km^2. Soils are usually old, heavily weathered oxisols or ultisols that are nutrient poor. Oxisols are the oldest and most heavily weathered of the earth's soils. They are highly permeable, low in nutrients, and lack distinctive horizons. These soils are generally red, indicative of iron (Fe) oxidation, or yellow from aluminum (Al) oxides. Ultisols are similar to oxisols except that they have differentiated horizons, which can result in a change in pH and texture with depth. The soils in lowland rain forests are so nutrient poor that the high biomass of these forests is, in fact, the major pool of regenerative nutrients.

The next category comprises the montane rain forests that can range from 1,000 to >3,000 m in elevation and usually transition into montane tundra at higher elevations. Montane rain forests are frequently divided into lower montane and upper montane. The lower montane forests cover about 1.8M km^2 and the upper montane forests about 1.5M km^2. Soil fertility is often much higher in these regions, as many of them derive from volcanic origins. Temperatures are cooler, which means less prevalence of endemic tropical diseases such as malaria. For these reasons, population densities are usually much higher than in lowland forests. High population density exerts great pressure on a limited resource base, which is why montane forests have experienced the most rapid rate of deforestation of any major biome (FAO 1999).

Several generalizations can be made in relation to forest structure when movement from lowland forest to upper montane zones is considered. Shrub layers become more conspicuous, and the number of woody vines and the size of canopy dominants decrease. Although much more biologically diverse than nontropical forests, montane forests contain less biodiversity than lowland forests.

Tropical evergreen forests are under intense human pressure throughout the world. In Africa most of it is due to conversion to agriculture, while in the Amazon large tracts of primary forest are being converted into pasture. Poorly monitored and regulated commercial logging is a major threat in most of the tropics. The objective is usually to liquidate the most valuable species as quickly as possible, with little regard for future stand structure and productivity.

Tropical Deciduous Forests (tropical xerophytic forests). This biome is the tropical counterpart to broad-leaved temperate mesophytic forests. Whereas the leafless season in the temperate regions corresponds to day length, leaf fall in the tropics is a function of precipitation. Annual precipitation in these areas is sufficient to sustain a closed canopy forest, but not enough during certain times of the year for all species to retain their foliage. Leaf fall and flowering begin just before start of the dry season.

On a global scale these forests cover an area of 5.5M km^2. They often occur on the borders of evergreen forests and are found from Mexico into South America, Africa and southeastern Asia, including India and Bangladesh. Species diversity is less than in evergreen forests and the canopies tend to be shorter and slightly more open. In all parts of their ranges, tropical deciduous forests have been subjected to human pressure for grazing, agriculture and exploitation of valuable timber species. These forests, among all the forest biomes, have historically been the most negatively affected by humans. Today they are the most endangered of the world's forest biomes, with only a small percentage of their original surface area remaining undisturbed.

2. Plantations

Forest plantations are defined as tree crops raised artificially by sowing seed or by planting seedlings (or cuttings; Evans 1992). Plantations can be established with either indigenous or nonindigenous ("exotic") species and can be grown for industrial, community/social or conservation objectives. The importance of plantation forests in the global forestry picture is steadily increasing. Reasons include faster growth rates than for natural forests, familiarity with management and processing, relatively short rotation ages (cutting cycles), and much greater cost efficiency in the management and harvest of the product. In theory, increased use of plantations could substantially reduce pressure on natural forests (Evans 1992; Nambiar and Brown 1997).

In 1997, plantations represented about 3.8% of the world's forest area, covering 130M ha of land. Approximately 54% of this area are found in developing nations. Countries that have the lowest percentage of plantations relative to total forest area include Canada, the former Soviet Union and Indonesia (2%–5%). Countries in which plantations represent a mid-range percentage (10%–20%) include the United States, New Zealand, South Africa and Chile; countries with higher percentages (>20%) include Japan, China, North Korea and India. Japan has the highest percentage of any country, with 44% of its forests in plantations (FAO 1999).

From 1965 to 1990, there was a six-fold increase in forest plantations worldwide (Evans 1992). The current rate of plantation afforestation/reforestation in the tropics is doubling every 10 years. In addition to the countries listed above, some of the nations that have initiated vigorous plantation forestry programs during this time include Australia, Malaysia, Portugal, Spain, Thailand, Uruguay and Venezuela (FAO 1999). The importance of forest plantations will likely continue to increase as countries struggle to conserve remaining natural forests while addressing domestic and international demands for wood and wood products.

3. Major Uses of Forests and Forest Products

Forests provide numerous industrial and subsistence products, contain most of the planet's terrestrial biodiversity, and furnish a wide range of ecological services (e.g., water retention and filtration) to a growing global population. Some of the better-known industrial uses of forest trees include sawn logs for lumber, shipbuilding and furniture; veneer for plywood, containers and construction; and pulpwood for paper products, textiles and clothing. Trees are also used for electric utility transmission poles, particleboard and railroad ties (sleepers) and as a source of gums, resins and oils (Table 4).

On more regional or local levels, non-industrial forest uses can be even more important. Throughout most of the developing world, for example, wood and charcoal made from wood are still the primary energy sources for cooking, heating and other household uses. This trend is decreasing somewhat, but wood will continue to be relied on as a readily accessible fuel source. Forests also provide a wide range of other valuable non-timber products such as fruits, nuts, honey, ropes, baskets and wax. Some species produce excellent fodder for livestock; others fix atmospheric nitrogen into their roots and are commonly used as natural fertilization in rotational agricultural systems (FAO 1999).

Costanza et al. (1997) estimated the value of the services provided by the world's natural ecosystems at $35 trillion/yr. Forests provide many of these services. Water catchment forests are a continuous source of clean water in mountainous areas. They control runoff and have very low erosion rates compared with all other land uses. Well-managed forests contain the highest levels of terrestrial genetic diversity, some of it with medicinal potential. Protecting this diversity is a key element in the strategy to better conserve and manage the world's remaining forests.

Table 4. Potential harvestable products, uses and natural services provided by forest ecosystems of the world.

I. Industrial Uses

A. Saw logs: Lumber, joinery, furniture, packing, mining, shipbuilding, construction, sleepers
B. Veneer Logs: Plywood, furniture, containers, construction
C. Pulpwood: Newsprint, paperboard, paper containers, textiles, clothing, packaging pulp
D. Residues: Particleboard, wastepaper, floorboard
E. Poles: Transmission poles, pitprops, pylons
F. Charcoal: Steel making, PVC, dry cells, chemicals
G. Extractives: Turpentine, gums, resins, oils, tannins, distillates

II. Indigenous Consumption

A. Fuel wood and charcoal: Cooking, heating, household uses
B. Agricultural uses: Shifting cultivation, forest grazing, fodder, N_2-fixation, mulches, fruits/nuts, game meat
C. Building poles: Construction, fencing, furniture, scaffolding
D. Saw milling and pit sawing: Joinery, furniture, construction
E. Exudates: Honey, sild, wax, sap
F. Weaving materials: Ropes, string, baskets, furniture
G. Special wood, ash: Carvings, chemicals, incense, glass making

III. Ecological Values

A. Catchment and watershed protection: Runoff control, potable water, irrigation, soil fertility
B. Ecology and conservation: Genetic conservation, recreation, tourism, landscape
C. Erosion control: Shelter belts, windbreaks, dune stabilization, reclamation of degraded land

The value of tropical forests in particular for biodiversity conservation has gained greater recognition as research reveals additional facts about complex natural ecosystems and as tourists spend more time and money to experience them firsthand. Interest in tropical forest tourism and recreation has grown rapidly over the past 25 years in both the developed and developing world. Tourism is one of the world's highest growth sectors and an increasing amount of tourism revenues are being generated by forest-based activities.

For the year 1996, extractive forest uses consumed about 3.36 billion m^3 of wood, roughly equivalent to 1% of the world's total growing stock. Of the total, 63% was used for fuelwood and other local domestic needs (FAO 1999), and the rest for industrial roundwood. Geographically, the developed countries consumed 33% for fuelwood and domestic uses. In contrast, in the developing countries 81% was consumed for fuel and the remaining 20% for industrial purposes. Global fuelwood demand is projected to rise 1.1% per year until 2010; industrial round-wood demands will increase by 1.7% during the same time.

Though it is difficult to estimate global future demands for wood products, a number of factors will directly affect the demand. The most obvious is the world's population growth rate, which is still increasing in spite of near-zero or even negative rates in many developed countries. Some projections place the world's population at 10 billion by the year 2050, or just under two times what it was in 1990 (5.28 billion; FAO 1999). It is virtually certain that the demand for wood products will increase along with population.

A second issue is standard of living. Generally, the demand for wood products increases as standards of living increase. In some developing countries the standard of living is increasing rapidly, while in developed countries it is increasing only slightly. As developing countries continue to close this gap, the demand for wood products globally will increase.

Current production/consumption rates indicate one consistent trend: all regions of the world, with the exception of Asia (excluding Russia), are producing more wood than they are consuming. Asia is the current exception, with production rates at just less than 300M m^3/yr and annual consumption a bit more than 500M m^3. Asia is projected to remain a net wood-product-importing region through at least 2010 (FAO 1999).

Certain forces can decrease the demand for raw wood, including development and application of technologies designed specifically for that purpose. Some of these include better utilization of smaller trees and residues, more efficient pulp and paper processes, increases in the use of recycled paper and substitutions from other industries (e.g., metal and concrete for construction, electronic publishing to reduce paper). Although most wood substitutes actually cost more to produce in terms of fossil-fuel consumption than equivalent natural wood products (Brown 1996), compelling arguments can be made for their expanded use.

4. Deforestation

The rate of loss of natural forest area from 1980 to 1990 was 15.5M ha/yr. Between 1990 and 1995 the loss rate was 13.7M ha/yr, with a total loss of 56.3M ha worldwide for the 5 years (FAO 1999).

The "loss" of 56.3M ha is slightly misleading, however, since an actual loss of 65.1M ha took place in developing countries. This was partially offset by a small net increase of 8.8M ha in developed countries. In any case, it is clear that boreal and temperate forests are expanding, albeit at modest rates, while most of the world's net deforestation is taking place in the tropics. As noted earlier, there is debate over how "forest" should be defined for inventory purposes, which has confused the issue of how much carbon is released via deforestation (see Houghton et al. 2000 and Nepstad et al. 1999 for details).

Since 1995, a series of climatic phenomena have contributed significantly to deforestation. In 1997 and 1998 El Niño-related fires destroyed millions of hectares of forestland throughout the world. Some of the more notable fires were in Brazil, which suffered an estimated loss of 2M ha, and Mexico and Central America, which together lost about 1.5M ha. In Indonesia, Sumatra and Kalimatan reportedly lost close to 2M ha; the state of Florida reported losses of about 200,000 ha. In the northeastern United States, severe ice storms damaged trees over an area covering 7M ha (FAO 1999). Some scientists suggest that these events are a direct result of global warming, while others maintain that there is no compelling evidence.

Of all the world's forest biomes, tropical forests are undergoing the most rapid change. Much of it can be attributed to the expansion of subsistence agriculture in Africa and Asia, as well as to large economic development programs involving resettlement and agriculture in Latin America and Asia (Watson et al. 1997). Increased timber harvesting often leads to local extirpation of economically and ecologically important species. Tropical forests also suffer unnecessarily heavy damage and loss from harvesting operations that are poorly planned and regulated. This is because the silvics of most tropical forest species are poorly understood and because many regulatory agencies responsible for overseeing forestry activities are often understaffed and insufficiently equipped. These conditions often result in morale and accountability problems.

Roads and trails developed for timber extraction provide easy access to previously inaccessible areas for those engaged in mineral exploitation, wildlife harvesting or other activities. Opening new areas often leads to introduction of domestic animals (carrying pathogens that are sometimes transferred to native fauna). Because forest edges and interiors of degraded forests dry out, this activity also greatly increases the incidence of wildfires from human ignition or natural storms (Nepsted et al. 1999).

The cumulative effects of these factors place tropical forests at the greatest short- and long-term risk of all the forest biomes.

Appendix 6 Options for Mitigating Global Climate Change through Forest Management: Maintaining and Creating Sinks

1. Conserving Carbon in Existing Forests

A. <u>Improved Silvicultural Practices</u>

Silviculturalists have four general ways of exploiting a forest, ranging from complete removal of the forest cover (clear-cutting), to harvesting of specific tree species and size classes (selection cutting) with intensities as low as one or two stems per ha (Smith 1961). The other two methods, seed-tree and shelterwood cutting, fall between these extremes. The seed-tree method leaves individuals or groups of trees on the site to serve as a source for natural regeneration. Usually only a small portion of the original stand is left; after a new tree layer is established, the seed trees are removed. Shelterwood cutting involves gradual removal of portions of the stand at specified intervals, with the objective of establishing an understory of new trees by the time the cutting cycle is completed. The chief difference among the four approaches is the degree to which living woody biomass (mainly tree stems) is removed from the forest at any given time, and therefore the nature of the residual or subsequent stand.

Many modifications of these four systems have been applied to various forests around the world, particularly in the temperate zone. Although clear-cutting was once carried out extensively throughout all the forest biomes, its use is in rapid decline as it is viewed by many as a destructive harvesting method. Clear-cuts are usually unpleasant aesthetically, and, if conducted at inappropriate sites (e.g., on steep slopes or poorly developed soils), can lead to soil loss and other negative environmental consequences. However, for a number of shade-intolerant species that grow naturally in even-aged stand conditions, or for plantations, clear-cutting still may be the best harvesting method to assure rapid reestablishment of a new forest crop. Even regeneration of some tropical tree species, such as the Central American mahogany (*Swietenia macrophylla*), requires clearing areas of considerable size (Snook 1996).

Other silvicultural treatments are used to improve the productive capacity of both natural forests and plantations and to provide a higher-quality end product (Nambiar and Brown 1997). These treatments may include thinning, pruning, fertilization, weed control, protection from pathogens and fire and artificial regeneration (e.g., planting). For example, a thinning is often carried out to bring a stand of trees to a more optimum stocking density. It is designed to eliminate less productive stems that compete with healthier trees for limited nutrients and sunlight. The remaining trees normally respond by growing at accelerated rates for extended periods.

Pruning may be conducted for a number of reasons (e.g., enhanced wood quality, reduced incidence of disease), in addition to increasing productivity. Many species retain lower limbs, which are often shaded and not as productive as the upper parts of the tree crown. Cutting these out often promotes new foliage growth in the upper crown, which in turn increases productivity. Light interception, and hence photosynthesis, becomes more efficient as the percentage of needles in the upper layers of the canopy increases (McCrady and Jokela 1998).

Fertilization and weed control are both designed to increase the growth of a forest stand. Fertilization accomplishes this simply by adding nutrients to the site, which will benefit both the trees and other vegetation. Weed control limits nutrient, water and light competition to trees by suppressing or eliminating other vegetation. Additive value can frequently be obtained with a combination of treatments, such as weed control and fertilization (Colbert et al. 1990). Any resultant increase in tree biomass represents increased carbon storage (ignoring the fossil-fuel energy used in the processes to develop fertilizers, herbicides and so forth). Most silvicultural treatments are considered during the life of a production forest system, whether it is a natural stand or a plantation. However, plantation management usually results in a greater expenditure of effort and resources over a management cycle (or rotation).

The best harvesting system for a particular forest from a sustainable productivity standpoint is generally one that mimics, yet accelerates, the natural disturbance and successional regimes of a stand. For example, in temperate forests, clear-cutting could be the method of choice for less complex forests (with one to four dominant species) that are naturally found in more or less even-aged conditions following intense wildfires. Generally, as the numbers of species and age classes of a forest increase, the method of harvesting moves more toward selective cutting methods.

In temperate forests, these silivicultural systems have been tried and tested over a wide range of ecosystems. Decades of applied research and monitoring have been required to understand the silvics of individual species and the ecology of individual forest types. Most, but not all, temperate forest ecosystems are understood well enough to predict rather accurately how they will respond to a variety of different silvicultural treatments. In the context of North America, some of the most reliable data have been generated from the least complex and more intensively managed ecosystems (e.g., pine forests of the southeastern United States, coniferous forests of the Intermountain region and the Pacific Northwest of Canada and the United States, and boreal forests). Less is known about the management and productivity of temperate deciduous and mixed forests (Landsberg and Gower 1997). Currently the greatest debates concerning temperate zone forestry focus on the types of allowable uses and levels of management intensity appropriate for publicly owned lands (e.g., the national forests of the United States; Franklin 1999).

The situation in the tropics is much more daunting. Economic considerations (e.g., poorly developed markets, lesser known species and products, high transportation costs, government subsidies for competing land uses) are the overriding force that has determined how most of these forests are treated. The norm has been to cut and move on, with little or no regard for regeneration and subsequent stand development (as was the historical case in Europe and North America). Though some rates of country deforestation appear to be diminishing slightly, this is still the approach taken in many, if not most, developing countries.

Tropical cutting systems have usually been either large-scale clear-cuts or intensive selective cutting where all valuable trees are removed. The latter is commonly called "hygrading "or "creaming off" where the best species and stems are removed, leaving only the less desirable behind. This of course leads to a vast reduction in diversity (at both the species and genetic levels) and productivity, as well as to changes in the forest structurally, physically (e.g., increased temperatures and lower humidity in the understory) and biologically.

More progressive harvesting techniques, referred to as reduced-impact logging (RIL), are viewed as having great potential for more effective management of natural forests (Pinard and Putz 1996). The premise of RIL is that reduced damage to residual vegetation following logging operations will lead to retention of more carbon in the remaining trees. It also assumes that soil damage will be reduced, thereby safeguarding the carbon storage of forest soils. This in turn favorably predisposes the site for rapid regeneration and faster growth of residual trees, leading to subsequent higher rates of carbon accumulation. Thus it is conceivable that some harvesting could occur in such a forest, with the carbon removed during harvest replaced by accumulation in regrowth before the next harvest is carried out (i.e., sustained yield).

One study conducted in Malaysia indicated that the difference in remaining biomass one year after logging was 23%, with 44% of the pre-harvest biomass left behind following conventional harvesting, compared with 67% following RIL. Most of this difference was due to the destruction of fewer trees during the harvesting process (Pinard and Putz 1996). The past decade has seen the development and implementation of a number of RIL demonstration projects in the tropics. As results become available, the relative importance of RIL in the management of forest carbon will be better understood and appreciated.

The initiative to certify forests and their products is related to the improvement of silvicultural practices worldwide. Forest certification has gained increasing popularity during the past decade, and is being tested and implemented throughout the world at various scales. The underpinning theme is that consumers are assured that a forest product has been produced using practices that meet fundamental ecological and social standards (Kiker and Putz 1997). The system relies on developing a set of relationships between institutions (stakeholders) that are mutually agreed upon, and on reliable and continuous monitoring of each step within the process. The issues are complex, but when correctly implemented, certification has potential to provide positive incentives for better forest management (Ervin et al. 1996).

Research designed to directly address the connections between carbon storage and silviculture has been limited, although this field is gaining increased attention. A number of ongoing studies should provide additional information in the near future. For the moment, forest productivity and health will continue to determine which silvicultural practices gain the widest application. However, as the relationship between forest management and climate change becomes better understood, it is likely that future silvicultural recommendations will give greater consideration to carbon storage.

B. Forest Protection from Fire and Disease

Fire and disease account for the destruction of vast forested areas each year. Some years are worse than others, and the severity of the incidents is usually related to exceptional weather-related events. Fire and disease outbreaks often occur in relation to each other; forests disturbed by fire are weakened and more susceptible to insect and pathogen attacks, and the reverse is often true as well.

Forest fires of both anthropogenic and natural causes are common occurrences throughout most of the world's forests, especially during dry seasons. They are responsible for the rapid release of CO_2 (as well as other greenhouse gases, such as methane, carbon monoxide, and nitrous oxide). Fires are categorized in a number of different ways in different parts of the world (e.g., Figure 10).

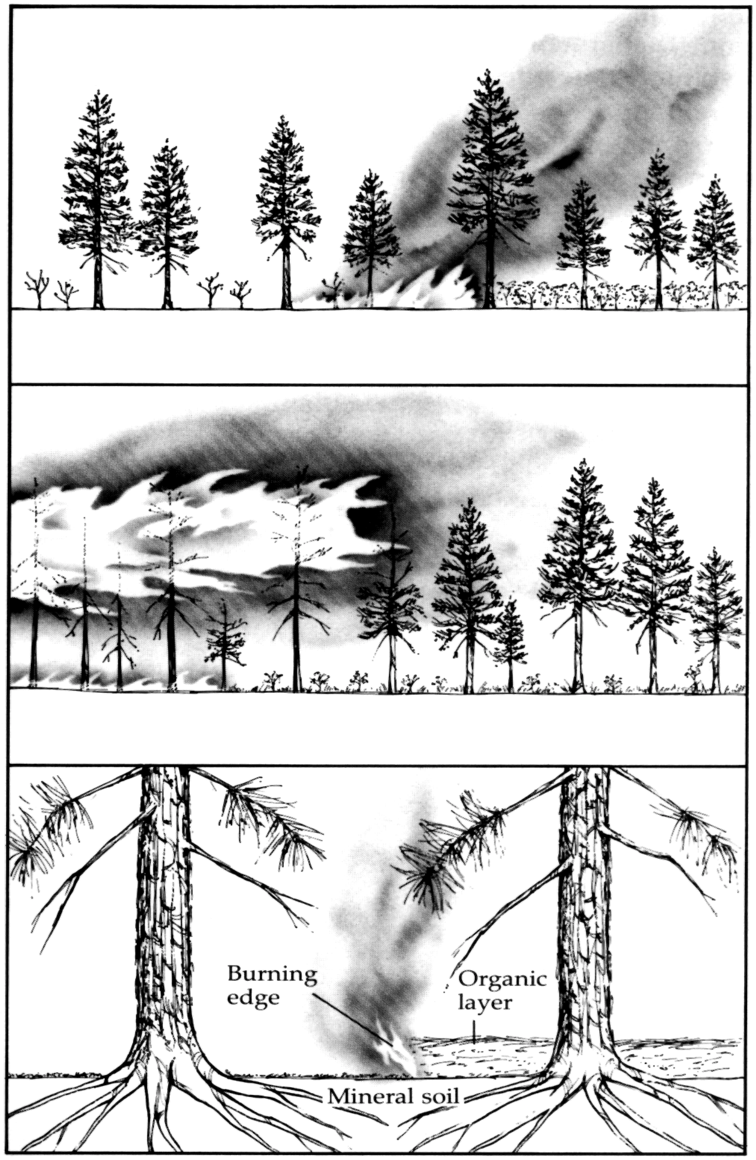
Much of the burning that takes place in the tropics is associated with land conversion or preparation of land for pasture use. Inability to control these fires is a main contributor to forest degradation and deforestation (Nepsted et al. 1999). Fires are also frequent in temperate and boreal forests; large tracts of forest are lost each year to uncontrolled wildfires, despite the more aggressive and effective use of protection methods in these areas.

The role of fire as a natural ecological process associated with forests has only recently been appreciated. In the United States, for example, forest managers traditionally viewed fire as a destructive agent that should be prevented and combated at any cost. This practice led to the buildup of exceptional amounts of forest litter and understory vegetation, which when dry supplied the necessary fuel for intense wildfires.

Increasingly, scientists and forest managers appreciate the positive role fires play in many of the world's natural and managed forests. The critical issue is determining the historic role of fire in specific cases, and then, if appropriate, how fire can be effectively used to help maintain a healthy and dynamic ecosystem. In many parts of the world, forest management agencies now regularly conduct controlled or "prescribed" fires to reduce litter accumulation and prevent large-scale forest destruction from more wildfires.

In addition to reducing fuel levels, prescribed fires release nutrients bound in slowly decaying litter (generally in temperate and boreal forests), stimulating the growth of remaining trees, which usually escape serious injury. Such fires also promote a vigorous post-fire understory, which often contains nitrogen (N_2) fixing species. Since N has a low heat of volatilization, it is usually lost to the ecosystem in proportion to the amount of carbon in organic matter consumed by the fire.

Insect and microbial pests can significantly contribute to forest degradation. Most "catastrophic" outbreaks are associated with monocultural plantations (i.e., only one species used to reforest an area), which are particularly susceptible to pest attacks and in which growth losses or mortality are especially noticeable and costly. Outbreaks are often associated with environmental stresses, such as droughts. In these cases, tree vigor is



(a)

Figure 10. Three general types of forest wild fires, surface (top), crown (middle) and ground (lower) (from Aber and Melillo 1991).

greatly reduced, which can promote the spread of insects and diseases and lead to tree mortality. Pest infestations can cause losses in forest productivity, meaning less carbon storage and lower accumulation rates. But it must be kept in mind that the natural biodiversity of insects and microbes is immense and that the roles they play are critical to forest functioning (e.g., as decomposers, as prey species for critical wildlife, or as predators controlling populations of other potentially damaging species). Most widespread damage to natural forests or forest species by insects or pathogens has been the result of introductions of exotic species (e.g., the gypsy moth, *Lymantria dispar*, in eastern North America).

In many countries, substantial resources have already been channeled toward increasing the effectiveness and efficiency of forest protection, usually in response to emergency wildfire situations, such as the El Niño fires in Mexico (1998), Indonesia (1987, 1993, 1997–1998) and Brazil (1998). Improved detection and preventative measures, such as prescribed burns, ground surveillance and use of remote sensing, will allow responsible governments and agencies to respond more rapidly to clearly threatening events.

C. Sustainable Forest Management

Sustainable forest management, as used in international forestry initiatives, is derived from the concept of sustainable development, adapted from the Brundtland Commission and further adapted to management of forest resources by the United Nations Conference on Environment and Development (UNCED) in 1992. The concept was refined by the U.N. Commission on Sustainable Development (CSD) and the Intergovernmental Panel on Forests (IPF). More recently, the FAO Committee on Forestry prepared a second draft of the strategic plan for management of the world's forests for the years 2000-2015 (FAO 1999). One of this committee's objectives is to develop and harmonize criteria and indicators for sustainable forest management.

The concept of sustainable forest management is at the same time simple and complex. Fundamentally, it focuses on activities that ensure a continuing flow of commercial and environmental benefits from forests. Interpreted in this way, sustainable forest management could actually enhance existing forest carbon storage by maintaining existing carbon stocks in forests and additional carbon in long-lived products removed from forests, while preserving the value of forests as sources of products, biodiversity and other natural functions (Putz 1994). This is a worthy objective, whether the desired outcome is wood production, biodiversity conservation, watershed management, carbon storage or some combination.

The complexity of sustainable forest management derives from the great diversity of the world's forests and differences among the cultures that interact with them. Although precise definitions can be difficult to agree upon, adherence to well-established ecological principles and sound forest management practices will promote conditions more favorable to long-term sustainable uses of forests.

Sustainable forest management has a social element, since it is a process that must start with consensus building among stakeholders (foresters, researchers, commercial interests, community representatives and other interested parties) and culminate in the development of a guiding management plan. The plan is completed in a participatory manner to reflect the input and concerns of the relevant parties. Though forest management plans exist in all sizes and forms, the participatory aspect of the process has too often been ignored or underutilized in many parts of the world. More recently it has been viewed as critical to the success of any forest management endeavor.

2. Establishing New Forests

New forests include plantations, agroforests, home garden plantings, enrichment plantings, urban tree plantings and substitution plantings, established in areas previously unforested. In terms of carbon accumulation rates, plantation establishment through afforestation and reforestation holds the greatest potential. However, the cumulative effects of these other activities are considerable as well.

A. <u>Afforestation and Reforestation</u>

Several different definitions for both afforestation and reforestation are used internationally. For this report, afforestation is the establishment of trees on land that has not supported trees for at least 50 years or more (Evans 1992). Reforestation involves planting trees on areas that have been more recently deforested. In an ideal situation, afforestation of marginal lands with fast-growing species is one of the most promising short- to medium-term land-use practices for sequestering carbon (as well as for providing wood products), as tree dry biomass is 50% carbon.

Stands of some tropical plantation species, such as *Eucalyptus grandis, Gmelina arborea* and some of the tropical pines, sequester carbon in biomass at rates much greater than any other land use. Most of these species are grown on short (5-20 yr) rotations, depending on the anticipated final product. Throughout their rotations they function as net carbon sinks.

Advances in forest genetics have meant large increases in growth rates over a rotation, compared with stands of unimproved trees, resulting in greater gains in the amount of carbon sequestered (Boyle et al. 1997). As tree improvement programs become more common throughout the world, such productivity gains could become the norm.

Of course, harvesting removes carbon from the ecosystem (although as noted above, the removed carbon represents storage for some period). Given the current state of plantation management, once trees are harvested there is usually a relatively brief time before the land is again forested, as most sites are prepared and replanted within a year. Therefore, periods of zero or negative carbon accumulation are short. In addition to accumulation of carbon in tree biomass, carbon accumulation in litter can be an important component of the annual carbon balance for many plantation systems (e.g., Clark et al. 1999). The net difference in carbon storage is best seen as the average carbon in biomass (including litter) over several rotations, compared with that in a previous or potentially alternate land use.

Plantation forestry has expanded at a rapid rate over the past 20 years (FAO 1999), a trend that will continue as the world's population increases and the demand for forest products follows suit. Additional forest products will be needed as many developing countries continue to increase their standards of living. In 1992, plantations provided 34% of the world's industrial wood products although they represented only 3.8% of the total forested area. It is projected that by the year 2005 plantations will contribute about 50% of the world's forest products. Vast plantations are already established or planned in many parts of the world. In the tropics alone, plantations are being established at a rate of 2.6M ha per year (FAO 1999).

B. Agroforests, Home Gardens, Enrichment Plantings and Urban Forests

As populations throughout the tropics rapidly increase and arable land becomes scarcer, "trees outside of forests" will gain even more importance. This is expected to be particularly true for parts of sub-Saharan Africa and Southeast Asia. The effectiveness of agroforestry as a means of storing carbon is difficult to assess. Although agroforestry plays a positive role compared with most tilled agricultural systems, it will generally result in much lower new carbon storage than most other forestry initiatives simply because of lower average vegetation plus detrital biomass.

Brown (1996) estimated the potential carbon that could be sequestered and stored as a result of global agroforestry activities between 1995 and 2050 at 7 Gt. This figure represents roughly 10% of the total projected to result from improved forest management practices, with most occurring in the tropics.

In much of the developing world, home gardens produce about 60% of food for families, using only about 25% of household energy. Trees are an important component of home gardens. In a recent study of Indonesian home gardens, it was estimated that total carbon levels were only slightly lower than those of secondary forests in the same area (MacDicken 1997).

Although inventory methods have been developed to measure carbon levels in agroforestry systems and home gardens (MacDicken 1999), very few such assessments have actually been made.

Several other tree-planting activities may help offset atmospheric CO_2 buildup. One is enrichment of degraded forested areas, normally associated with but not limited to the planting of valuable timber species in areas that have already been exploited. This is a well-established forestry practice in many parts of the world. In addition to enrichment planting of commercial forests with valuable tree species, direct seeding has been used in heavily degraded areas.

Some tree-planting initiatives have already been designed specifically to offset carbon emissions in degraded tropical areas. The objective is to locate non-forested or partially forested low-productivity sites where establishment of a plantation will not adversely affect the local community (e.g., by co-opting prime agricultural land). In many instances, offset plantings incorporate other objectives into the planning. During the past decade more than twenty offset projects have been initiated worldwide, mainly within the framework of the bilateral Activities Implemented Jointly (AIJ) program, as pilot projects with financial support from private companies aiming to offset increases in carbon emissions elsewhere (Watson 2000).

The Population Division of the United Nations (UNDP) estimates that there will be 3.3 billion people living in urban areas within the next decade (UNPD 1996). As the world's urban centers continue to grow at unprecedented rates, the trees and forests associated with these areas will be relied on to provide a steady stream of services, one of which is the storage of carbon.

The role of trees in urban environments is becoming much better appreciated. Urban plantings are regularly carried out to help combat air pollution, to moderate temperatures during the warmest and coldest months and to provide aesthetic comfort and relief (including sound buffering). Owing to their high and widely dispersed leaf surface areas, trees are particularly effective in intercepting and/or absorbing a wide variety of air pollutants (e.g., nitrogen oxides, ozone, sulfur dioxide (SO_2)), as well as CO_2. Urban trees also moderate water runoff and provide very important aesthetic amenities, wildlife habitat and products (e.g., fruit, firewood).

In addition, numerous other tree planting techniques can be used to save energy. Windbreaks are commonly employed throughout most of the world. As with urban forests, they can provide relief from heat during warm periods and buffer the impact of cold, desiccating winds during the winter. Boundary or perimeter plantings around homes, on farms or at workplaces can function similarly.

3. Product Substitution

Another way of reducing CO_2 emissions is by increasing the demand for wood products that could replace other less energy-efficient materials. The forest products industry is dynamic and constantly changing. New products are being developed from wood, wood wastes and residues that could store carbon for much longer periods of time than can current products. For example, production of an equally effective wood beam requires less fossil-fuel energy than does the production of steel, concrete or beams of other materials. Chemical treatment of timber, particleboard and other wood products usually greatly extends their lifetimes, thus contributing to longer-term carbon storage in more durable wood products.

The use of wood to replace fossil fuels is viewed as one of the most promising medium- to long-term strategies to accumulate carbon (Brown 1996). When carried out in areas that are either seriously degraded or have not been forested for a long time, it produces encouraging results. Not only do tree plantations sequester carbon rapidly, but the fuelwood then replaces fossil fuels. Fuelwood can be easily stored, which means that carbon is maintained at the same time a new crop is growing. Although the potential is great, it is still unknown just how widely fuelwood will be accepted as a replacement for fossil fuels. This will be determined to a great degree by advancements in technologies designed to convert wood fuels more efficiently and in environmentally sound ways, as well as by the relative costs compared with fossil fuels.

Gasification is the chemical process of converting a solid or liquid fuel into a gaseous fuel (Amin and Russell 1981). It involves a number of stages, beginning with superheated wood and ultimately producing combustible hydrogen and carbon monoxide gases. The United States, Sweden, Finland, England, Brazil and the Netherlands are leading research and development in this area. Some projects involve modifying existing coal-fired boilers so that biofuels can be used to reduce CO_2 emissions. Other more ambitious undertakings include the use of wood fuels for regional electrical generation.

It is anticipated that development of wood-fueled power stations could lead to increased economic development. In addition to producing electricity, establishment of large industrial plantations could provide net increases in rural employment as well as other new opportunities. This model is being considered in many other parts of the tropics and subtropical regions, with the hope of providing a clean (net-carbon-neutral) and stable energy source.

The international community will closely watch these and other similar undertakings to see just how effectively wood fuel (a renewable resource) can be substituted for fossil fuels (a nonrenewable resource), and how the substitution will affect remaining natural forests in a given country or region. If fossil-fuel reserves are soon exhausted, wood and wood products are likely to play a greater role in meeting global energy needs in the future.

Appendix 7 Measuring and Monitoring Forest Carbon

Some of the data used in this report were obtained using standard and well-tested methodologies and are quite accurate quantitative descriptions of carbon, its movements and its relation to the overall functioning of forests and global processes. Other data, however, were necessarily the output of models, or even our current best guesses. The accuracies and uncertainties associated with the data vary. Some measurements of forest carbon are direct (e.g., daytime net ecosystem CO_2 fixation made using eddy covariance, or the destructive determination of tree biomass in a plantation), while others rely on some measurable independent variable(s) that are more indirectly related to carbon (e.g., remote sensing imagery, forestry field inventories of tree diameters in natural forests). Models are often used to extrapolate measurements made at smaller scales (e.g., leaf or soil surfaces) to whole ecosystems. Understanding some of the different methods should help resource managers and decision-makers critically assess the validity of the estimates.

The purpose of this section is to introduce some of the most common methods currently used to estimate carbon in biomass and rates of annual carbon accumulation in relation to forest management. Some strengths and weaknesses are highlighted, particularly those that may have more direct application to mission planning, programming and decision making. Measurement scale is central to the structure of this section. Although they are presented separately here, various approaches are usually used together to help create more accurate estimates at particular scales.

1. Remote Sensing

Remote sensing produces images from sensors borne by aircraft, satellites or even ultralight planes, and can be grouped into two functional activities: data acquisition and data processing/interpretation. Some of the elements associated with data acquisition include the nature of the energy source used to generate the signal (e.g., reflected sunlight, radar waves, or laser or sonar signals); reflection and distortion caused by materials in the atmosphere between the energy source and the surface of interest; and the absorption or reflection of energy at the earth's surface. Operationally, the energy that reaches the aircraft or satellite is captured by a sensor. The sensor data are then either stored for later retrieval or transmitted in pictorial (analog, as in video imagery) or digital (as in LandSat imagery) format to a ground receiving station.

Data interpretation is accomplished by examining analog data visually or with an assortment of instruments or digital data using computers. Reference data from maps, field surveys (increasingly using the global positioning system, or GPS) and other sources are used as supplementary resources to increase the efficiency and spatial referencing of the interpretation.

The scales at which remote sensing can be an effective tool in management of the world's forests are quite variable. Satellite images provide the broadest geographical range of information. Enhancement of satellite images can provide reasonable resolution of land areas as small as 10 x 10m (e.g., SPOT), and they are the best means of monitoring, on a regional scale, changes in forested areas due to land clearing, agricultural use and disturbances from wildfires. At a general level of resolution, seasonal variation in vegetation (i.e., "greenness") can also be monitored with satellite imagery.

At intermediate scales, high-altitude infrared, color or black-and-white photos, or standard video film taken from fixed-wing aircraft, can provide greater detail. These images are quite effective for planning, implementing and monitoring forest activities at the stand level. More recently, regular 35 mm "over-the-counter" cameras and film (as well as digital cameras) are becoming more widely used in forestry, particularly for quick estimates of local deforestation rates (e.g., taking 1-2 days to cover an area of 100 km^2, depending on weather conditions; Slaymaker 1997). This imagery can be used on its own or in conjunction with the more expensive and less readily available higher-altitude imagery.

Although remote sensing is an increasingly effective way of characterizing spatial variation and temporal change in forested cover, it is much less able to accurately assess changes in forest structure (e.g., the vertical and horizontal distribution of vegetation components and biomass). Unfortunately, it is often at the structural level where forest degradation is taking place, as a result of selective logging and associated damage, progressive removal of understory vegetation when converting forests into agricultural land, or understory fires (Nepsted et al. 1999). Laser back-scattering is being investigated as a method for analyzing the vertical distribution of leaf area and biomass of forests (Lefsky et al. 1999); this same approach is leading toward commercial production of high-resolution digital terrain maps.

These same limitations make estimates of forest productivity (or carbon budgets) more difficult to assess from remotely sensed imagery. At this time, spatial patterns are mainly used as a basis for extrapolating information using process-based models. The launches of LandSat 7 in spring 1999 and of a new generation of sensors in January 2000 as part of NASA's Earth Observing System (EOS) promise rapid developments in this area.

2. Modeling

The use of modeling and its applications to forest management have increased considerably during the past two decades. Most of the conventional models are statistical, derived from field measurements of stem dimensions of trees in a particular forest. These models do not take into account physiological processes or the responses of forests to changing environmental conditions.

Most ecological models of forests are centered on carbon flow within the system. They are currently being tested and employed to project changes in the structure and productivity of forests at a range of spatial and temporal scales. Some models focus on tracking the absorption and partitioning of solar radiation, and how this relates to physiological processes in a forest. Others incorporate information on canopy structure (e.g., degree of homogeneity, layering, clumping), although most forest models treat canopies as homogeneous.

Certain models focus on individual tree structure and dynamics (e.g., reproduction, growth, mortality). These models usually begin with either open ground or an assumed initial forest cover type and then predict changes over time, given assumed nutrient, water and environmental regimes. Light availability, temperature and tree-to-tree competition can be factored into these models (e.g., Jupp and Walker 1997). Some models stress the relationship between environmental data from ground stations, remotely sensed data and ecosystem attributes such as leaf area index (LAI) (e.g., RHESSys; Coughlan and Dungan 1997). Other well-known models that are being used to estimate ecosystem processes include MAESTRO (Wang and Jarvis 1990), which calculates net photosynthesis and transpiration rates of individual tree crowns, and BIOMASS (McMurtrie et al. 1990), a layered canopy model, which focuses on radiation interception by foliage, carbon fixation by photosynthesis and the growth patterns of trees.

FOREST-BGC (BioGeoChemical) is a model designed to provide estimates of carbon, nitrogen and water cycling across a range of forest ecosystems, driven by remote sensing estimates of LAI and local environmental data (Running and Gower 1991). The radiation utilization efficiency (epsilon) model is based on a relationship between production of dry mass by a forest stand and the amount of photosynthetically active solar radiation absorbed by a canopy (Landsberg and Gower 1997; Waring et al. 1995).

The PnET model (Aber and Federer 1992) simulates whole-forest canopy carbon gain, based on a relationship between and maximum rates of leaf net photosynthesis and nitrogen concentration for dominant tree species.

New models are continuously being developed, and existing models are being modified to accommodate new sources and types of information. Models will increasingly be used to predict changes in forest structure and productivity for prescribed environmental conditions.

3. Eddy Covariance

Eddies are turbulent structures caused by winds interacting with surfaces underneath. They transport heat, water vapor, momentum, CO_2 and other gases back and forth between ecosystems at the surface and the atmosphere overhead. The method of measuring the net vertical exchanges of gases by the eddies is known as eddy correlation, or eddy covariance. The net flux, or exchange, of CO_2 (for example) to and from a forest is the product of the net vertical movement of air and the concentration of CO_2 in the moving air. This product for CO_2 is generally downward into the forest during the daytime and upward into the atmosphere at night (e.g., Clark et al. 1999). In contrast, for water vapor, the movement is almost always up during the day and zero at night.

Eddy covariance enables researchers to directly measure whole-ecosystem net exchanges over very short periods of time (seconds), which then can be accumulated to provide quite accurate estimates of the net gains and losses of carbon for forests over longer time periods. This approach is becoming the standard for CO_2-flux field measurements from specific forests, although continuous measurements over entire years are still very difficult to obtain.

The technology used to measure eddy covariance is more accurate in assessing instantaneous forest carbon balances than all other methods. However, there are some significant problems. First, the methodology is expensive and requires a high degree of technical training to set up. A typical station would have a wide range of meteorological equipment, towers tall enough to put instrumentation above the top of the canopy, and an energy source. Second, rain interferes with data collection, equipment maintenance is problematic, especially at remote sites, and line power (or high-output solar) is required for extended measurement periods. Models are generally used to extrapolate to non-measurement periods. There are significant differences in opinion on interpretation of some eddy covariance results, especially those obtained under atmospherically stable conditions at night or in complex topography, where, for example, carbon dioxide can drain laterally out of the ecosystem.

Currently about thirty semi-permanent stations regularly measure forest carbon fluxes in North and Central America (AmeriFlux) and Europe (EUROFLUX). Most are located in temperate forests (http://cdiac.esd.ornl.gov/programs/ameriflux/). Tropical regions are considerably underrepresented, as are great parts of the boreal zone. Even within the temperate zone, there are not enough stations to cover the range of representative forest ecosystems, much less their various developmental stages.

Results of eddy covariance measurements in the southern Amazon region (Rondonia; Grace et al. 1995) suggest that even mature, closed-canopy, humid tropical rain forests could be net sinks for atmospheric CO_2. Extrapolation indicated that these forests might provide a global CO_2 sink large enough to balance the global carbon cycle, although data from only one station are hard-pressed to support that degree of extrapolation. The NASA/LBA program is beginning CO_2 flux measurements in the mid-Amazon (http://lba-ecology.gsfc.nasa.gov/lbaeco/) and there is an AmeriFlux site in Costa Rica, as well.

4. Field Inventories

Development of field procedures for monitoring the contents and fluxes of forest carbon is relatively recent. However, most methods are derived from well-established inventory techniques used in forestry, ecology and soil science (MacDicken 1997).

Carbon inventories often begin by utilizing routine forestry measurements to calculate tree-stem volume, which is then used to estimate biomass. These estimates are much more uncertain as structural complexity (e.g., species composition, size variation among trees, occurrence of dead trees) of the trees and forest increases. Ecological surveys are used in conjunction with forest inventories to obtain biomass estimates of smaller-diameter classes and herbaceous vegetation. Measurement of litter accumulation is also a part of ecological surveys. The 50% factor is usually applied to dry-mass measurements to provide carbon equivalents.

Belowground carbon contents are extremely difficult to accurately assess. Inventory work involves core sampling or excavation, both very time consuming. Soil cores can be sent to laboratories for analysis, although there is some variation depending on the specific analytical methods used.

These measurements generally provide estimates of carbon pool sizes only (kg C/ha of already stored carbon), not of the rates of change in them (or carbon fluxes). Measuring changes over time in ecosystem carbon contents, or fluxes, is much more difficult, especially where long-term eddy covariance measurements cannot be reliably or realistically employed (i.e., most of the world's forests).

Permanent inventory plots are increasingly used for long-term monitoring of tree growth and mortality, especially for tropical forests in which trees generally do not produce reliable annual growth rings. The Smithsonian Tropical Research Institute (STRI) has established permanent plots in a selection of representative tropical forests worldwide, and many countries maintain permanent plots for forest monitoring (e.g., the U.S. Forest Service's Continuous Forest Inventory plots).

However, it is important to bear in mind that year-to-year changes in the carbon contents (or net fluxes) of mature forest ecosystems are always going to be extremely small compared to their carbon contents, making accurate estimates of incremental changes in carbon extremely difficult using routine ground-based field inventory techniques. What are normally conducted (for economic reasons as well) are periodic inventory measurements at 5–10 year intervals. These inventories provide forest managers and scientists with valuable cumulative productivity information.

In addition to providing detailed information about forests, field inventories represent the only reliable way of ground-truthing information generated by other technologies. Without good supporting field information, most of the data generated through remote sensing and modeling would be of very limited use (but see Prince and Goward 1995 for an approach to estimation of ecosystem carbon balances based solely on remote sensing). Integrating a system of well-developed permanent inventory plots with remote sensing data and carbon models will be a continuing priority for those concerned with global carbon.

Finally, fluxes of carbon from soils are even more difficult to accurately measure than those associated with vegetation and litter. Evidence to date suggests that unless a forest is being cut and replaced by a long-lived, non-forested land use, or former agricultural land is being afforested, the assumption that carbon in soil organic matter (i.e., non-root soil humus) is in steady state is realistic and appropriate.

5. Estimates of Ecosystem Carbon Balances

The net annual carbon flux for a particular forest ecosystem is the difference between CO_2 uptake for photosynthesis (termed gross primary production, or GPP, for a hectare of forest) and the CO_2 released by autotrophic (plant) plus heterotrophic (animal and decomposer) respiration. The difference between GPP and autotrophic respiration is known as net primary production (NPP; Landsberg and Gower 1997).

Photosynthesis at the leaf level and respiration of various tissues can be measured in the field using portable infrared carbon dioxide gas analyzers coupled with chambers that can be modified to fit on stems, branches and roots (Aber and Melillo 1991). Tissue-level measurements are often used by scientists to help validate data collected at other levels, or are incorporated into models for scaling up to whole ecosystems (e.g., Cropper and Gholz 1993). The additional deduction of heterotrophic (nonplant, mainly decomposer) respiration from NPP provides an estimate of the net ecosystem carbon gain, also referred to as net ecosystem production (NEP), the same process that eddy covariance aims to measure.

Several methods have been developed to measure soil CO_2 emissions (or "soil respiration"). Portable CO_2 analyzers attached to chambers over the soil and near surface eddy correlation systems are increasingly being used to estimate soil CO_2 fluxes (Aber and Melillo 1991). Raich and Nadelhoffer (1989) proposed a method using total soil respiration and litterfall measurements to estimate root respiration for mature forests presumed to be in steady state (NEP = 0).

Annual carbon balances for whole forest ecosystems are still relatively few in number in the literature. Table 5 contains examples from a range of forest types obtained using eddy covariance.

Table 5. Annual net CO_2 exchange rates (NEP) for some contrasting forest ecosystems.

Forest Ecosystem Type and Location	**Annual Net CO_2 Gain (kg C ha^{-1} yr^{-1})**	**Reference**
Pine plantation, Florida	6,140	Clark et al. 1999
Cypress wetland, Florida	490	Clark et al. 1999
Aspen, Alberta	1,600	Black et al. 1996
Hardwood, Massachusetts	2,200	Goulden et al. 1996
Hardwood, Tennessee	5,250	Greco and Baldocchi 1996
Beech, Italy	4,720	Valentine et al. 1996
Rain forest, Brazil	1,020	Grace et al. 1996

Appendix 8 Methodology for Deriving the Risk Factor

The risk factor for each forest biome and forest system has been derived from a number of studies carried out to determine the extent and condition of the world's forests. Four criteria are used to develop the risk factor for each biome/system: (1) deforestation rates from 1980 to 1995, (2) population densities associated with each biome/system, (3) protected-area status and (4) potential negative effects from climate change.

The risk-factor scale ranges from 0.0 (which would indicate that conditions are optimal for this forest biome/system to flourish) to 2.5 (the highest level of risk under the current conditions). A value of 1.0 on the scale indicates a steady-state condition and is the baseline for calculating the risk factor.

The deforestation rates are from the FAO State of the World's Forests report (FAO 1999). The summary rates for the developed and developing world are used for the non-tropical and tropical forest biomes/systems, respectively. Between 1980 and 1995, forests of the developed world have increased in area by about 2.7% while forests of the developing world have been reduced by 9.1%. Each percentage point related to deforestation/afforestation/reforestation is equivalent to 0.1 point (either + or -) on the risk-factor scale. Rounding the percentages off, the deforestation rate for all tropical forest biomes adds 0.9 to the 1.0 baseline for an initial risk factor of 1.9. The 2.7% expansion rate is rounded down to 2.0% rather than up to 3.0% for all temperate forest biomes since there are some temperate forests in the developing world. Therefore, for temperate forests, 0.2 is subtracted from 1.0 to provide an initial risk factor of 0.8.

The second criterion is the population density associated with the biome/system in question, which are taken largely from the World Conservation Monitoring Center's (WCMC) forest-area-to-people (ratio) database.

For the risk factor, the population density criterion is broken down into three broad categories (low, medium and high), and each is assigned a value. Low population densities in and around a forest biome imply less risk and are given a value of 0.0. Medium population densities are given a value of 0.1, and high population densities are assigned a 0.2 value. This value is added to the deforestation value, completing two of the four steps in determining the final risk factor.

The third criterion is protected-area status. This information comes from WCMC's global assessment of the ratio of forests to protected forests. The range in forests under protected-area status is considerable across the biomes (deciduous, needle-leaved forests within the boreal forest and temperate coniferous biomes have only about 1% of the forests in protected areas, while one subset of the temperate evergreen broad-leaved biome has almost 23% of the forests in protected areas). The risk value for protected-area status is calculated either by adding to or subtracting from the cumulated value in the following manner:

Percent of Biome in Protected Areas	Risk Value
0–5%	+ 0.2
6–10%	+ 0.1
11–15%	0.0
16–20%	- 0.1
>21%	- 0.2

The fourth criterion is the potential negative effects from climate change to a particular biome. This value is taken mostly from model projections (Beniston and Fox 1996). As indicated earlier in this report, it is projected that the boreal zones will be affected most by climate change, followed by the temperate areas, with the least disturbance expected in the tropics. For these reasons boreal forests have been assigned a risk value of + 0.2, temperate forests + 0.1 and tropical forests 0.0. This value is added to the other risk values in determining the final risk factor.

As an example, consider the risk factor for high-altitude (1,500m+) tropical evergreen forests:

Criteria	Risk Value
Deforestation rates (tropical value)	+ 0.9
Population density (among the highest in the world)	+ 0.2
Protected-area status (about 16% of the forests are in protected areas)	0.0
Potential impacts of climate change (tropical value)	0.0
Total risk value	+ 1.1

This value is added to 1.0 (steady state), providing a final risk factor of 2.1.

The same procedure was used to determine the risk factors for all the other forest biomes/ systems. The methodology was modified for agroforestry/home gardens and urban forests, since protected-area status does not apply if it is left out of the calculations. Table 6 contains all the risk values for the forest biomes/systems presented in this report.

Table 6. Risk values for the four selected criteria and final risk factors for each forest biome/system (risk values are added to steady-state factor of 1.0).

Forest Biome/System	Deforestation	Population	Protected Area	Climate Change	Risk Factor
Boreal	- 0.2	0.0	+ 0.2	+ 0.2	1.2
Temperate deciduous broad-leaved	- 0.2	0.0	+ 0.2	+ 0.1	1.1
Temperate coniferous	- 0.2	0.0	+ 0.1	+ 0.1	1.0
Temperate mixed	- 0.2	0.0	+ 0.1	+ 0.1	1.0
Temperate evergreen broad-leaved	- 0.2	+ 0.1	- 0.1	+ 0.1	0.9
Tropical lowland evergreen	+ 0.9	0.0	0.0	0.0	1.9
Tropical mid-altitude evergreen	+ 0.9	+ 0.1	0.0	0.0	2.0
Tropical highland evergreen	+ 0.9	+ 0.2	0.0	0.0	2.1
Tropical deciduous	+ 0.9	+ 0.2	+ 0.2	0.0	2.3
Plantations	- 0.1	0.0	- 0.2	0.0	0.7
Agroforestry/home gardens	- 0.2	+ 0.1	N/A	0.0	0.9
Urban forests	+ 0.3	+ 0.2	N/A	0.0	1.5

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